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CONTENTS OF VOLUME LIV

NUMBER 1

NUMBER 2

NUMBER 3

NUMBER 4

NUMBER 5

NUMBER 6

VOLUME LIV NUMBER 1

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AN EXAMPLE OF THE DEVELOPMENT OF CLEAVAGES

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ABSTRACT

An attempt is made to follow the development of secondary structures in a slate, the Martinsburg formation in Warren County, New Jersey. In part of the area discussed, the structures are of the type common in slate regions with overturned folds, axial-plane flow cleavage, and the development of grain. Grain is believed to result from stretching of quartz grains in *a* rather than from tension normal to *ac* during elongation of the fold axis. Fabric analysis emphasizes the importance of elongation in *a*.

In the southern portion of the area described, other structures have been superimposed as a result of the movement of a thrust fault. The bedding is refolded, the flow cleavage is folded, and fracture cleavage parallels the axial planes. Closer to the thrust, antithetic rotation of the slate along the fracture cleavage has almost destroyed all evidence of the earlier flow cleavage and has caused the fracture cleavage itself closely to approximate flow cleavage in microscopic and megascopic appearance.

INTRODUCTION

The preservation of minute secondary structures is more nearly complete in slates than in almost any other rock. This is especially well illustrated by the highly deformed Ordovician slate belt running from northern Pennsylvania into New Jersey. C. H. Behre, Jr.,[1] has shown that in this area the many megascopic structures make structural interpretation far more complete than is usually possible. This paper summarizes an investigation of the New Jersey slates made by the writer in 1938–40.

GENERAL DESCRIPTION

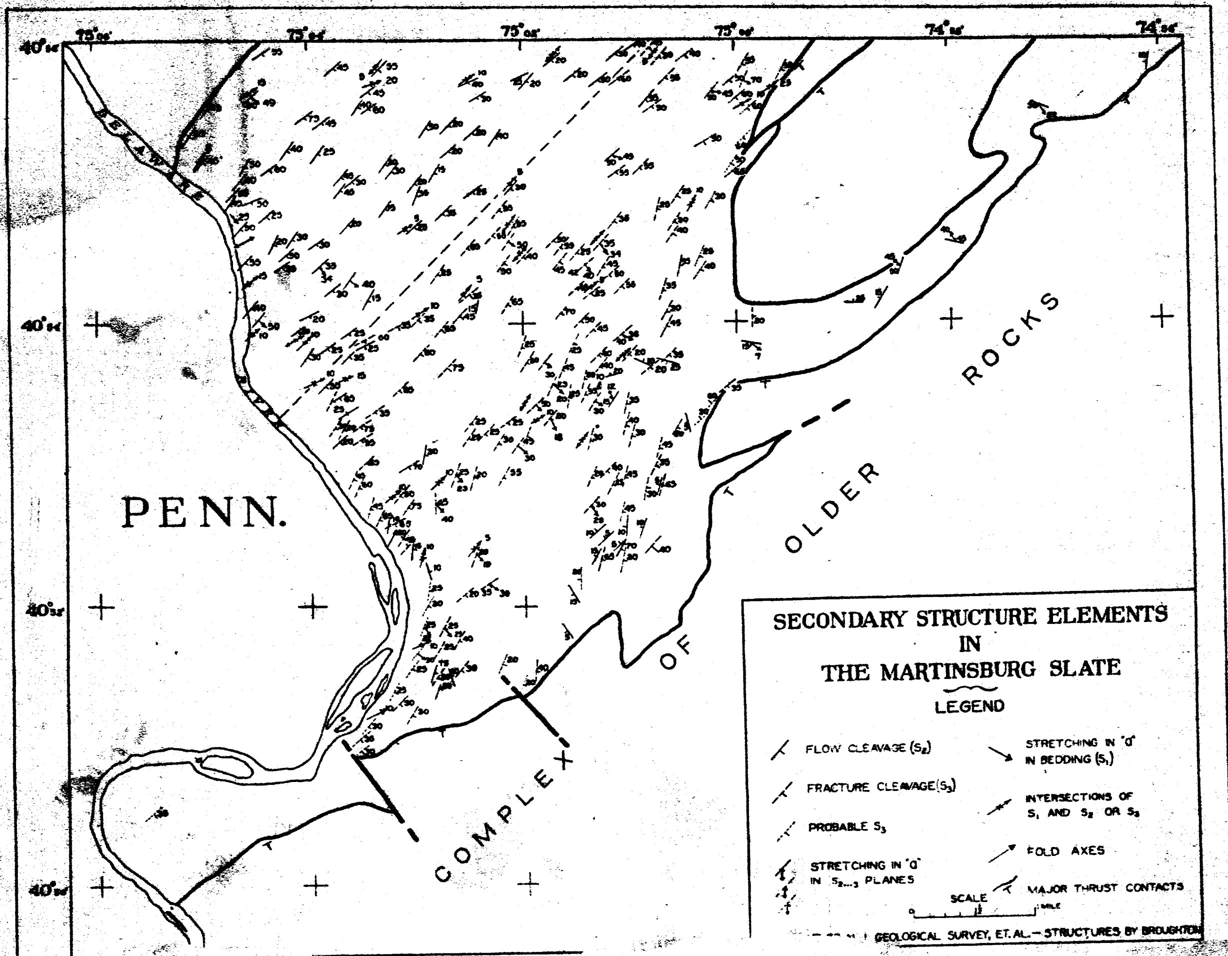
The Martinsburg formation, of middle and upper Ordovician age, extends northeast across New Jersey from latitude 75° 05′ west to latitude 74° 35′ west, in a belt approximately 7 miles wide. For about two-thirds of that distance a septum of older Kittatinny limestone (Allentown and Beekmantown) divides the belt into two parts. Elsewhere the Martinsburg formation is found only in small areas which have been downfaulted between pre-Cambrian ridges. The region discussed in this paper comprises an area of about 33 square miles south of the limestone band and immediately across the river from the Pennsylvania slate belt (Fig. 1). The thickness of the Martinsburg, where estimated along the Delaware River, ranges from 3000 to 11,000 feet.[2,3]

Three planes of reference can be distinguished in the slates; the bedding, the

[1] "Slate in Pennsylvania," *Pa. Geol. Surv. Bull. M16* (4th ser., 1933).

[2] G. W. Stose, "Unconformity at the Base of the Silurian in Southeastern Pennsylvania," *Bull. Geol. Soc. Amer.*, Vol. XLI (1930) p. 634.

[3] P. 137 of ftn. 1.


SECONDARY STRUCTURE ELEMENTS
IN
THE MARTINSBURG SLATE
LEGEND
FLOW CLEAVAGE (S_2)
FRACTURE CLEAVAGE (S_3)
PROBABLE S_3
STRETCHING IN 'a' IN $S_{2...3}$ PLANES
STRETCHING IN 'a' IN BEDDING (S_1)
INTERSECTIONS OF S_1 AND S_2 OR S_3
FOLD AXES
MAJOR THRUST CONTACTS
SCALE
GEOLOGICAL SURVEY, ET. AL. — STRUCTURES BY BROUGHTON
PENN.
DELAWARE RIVER
OLDER ROCKS
OF
COMPLEX

flow cleavage, and the fracture cleavage. They will be referred to as S_1, S_2, and S_3, respectively. All structures are described by reference to a triaxial coordinate system. Axis *a* represents the direction of transport, whether it is in a bedding plane, a cleavage, or elsewhere. Axis *b* is normal to it and parallels the fold axes. Axis *c* is normal to the *ab* plane.

Compass directions are referred to a circle of 360° rather than to four quadrants of 90° each.

STRUCTURE

BEDDING (S_1)

The formation has been subdivided lithologically by Behre[4]

into a lower, a middle, and an upper part. The lower part is characteristically a banded clay slate, though there are also thin sandstone beds. The middle member contains sandy beds as its most typical facies, though some truly slaty beds are also found in it. The uppermost member is banded like the lower, but there is less sand and the undivided beds are much thicker. The differences between these subdivisions are relative, and in areal mapping the line between them is drawn with difficulty.

A difference of opinion exists as to the actual occurrence of this upper member. Stose[5] believes that it is simply the lower member repeated by folding. Since the question can have little or no bearing on the subject of the slate structures, it will not be discussed further here.

Numerous thin sections of the slate were studied under the microscope. They show that the most common facies of the slate are (1) sericitic slate with carbonaceous matter and a small percentage of quartz and (2) beds made up predominantly of angular quartz grains. The latter beds are seldom more than 2 or 3 feet thick. A very noticeable structure of these sandy beds is an intricate folding, completely contained within the bed and emphasized by contorted films of black, probably carbonaceous, material. These folds seem to bear no regular relation to the axes of deformation and show no parallelism among themselves. It was not possible to collect a satisfactory specimen for petrofabric analysis. W. H. Twenhofel[6] assigns structures of similar appearance to deformation during sedimentation. W. H. Bucher (personal correspondence, 1944) calls this "interstratal flow," differential movement between beds connected with unequal compaction of layers of different mobility.

Carbonate lenses occur locally in the slate. They are very minor features stratigraphically but are important structurally and therefore are discussed in the sections on folds and fold axes.

FOLDS AND FOLD AXES

Throughout the area the bedding has been folded and overturned to the northwest. Behre's areal map (1933, Pl. 24) seems to indicate that these small folds are only minor features. He shows the entire slate belt between the overthrust contact on the south and the limestone band on the north as one major syncline. The whole area can therefore be thought of as a synclinorium.

The fold axes most commonly pitch 5°–20° to the northeast. At a few localities they are horizontal, and rarely pitch to the southwest.

In the highway cut along the Delaware River between Columbia and Delaware, New Jersey, the slate is well exposed. Figure 2, *A*, is a diagram of the poles of bedding planes measured in this

[4] P. 136 of ftn. 1.

[5] Ftn. 2.

[6] *Principles of Sedimentation* (New York: McGraw-Hill Book Co., Inc., 1939), p. 529.

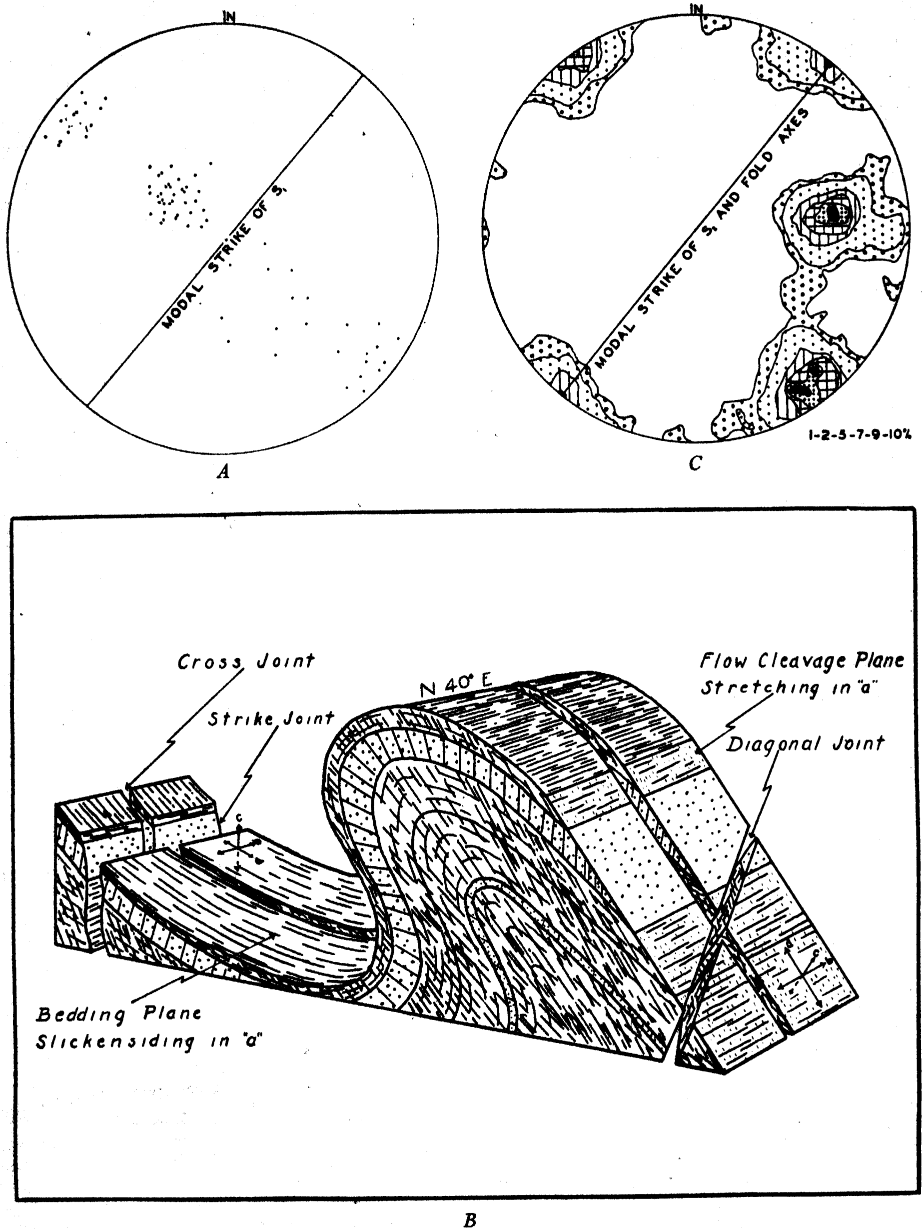


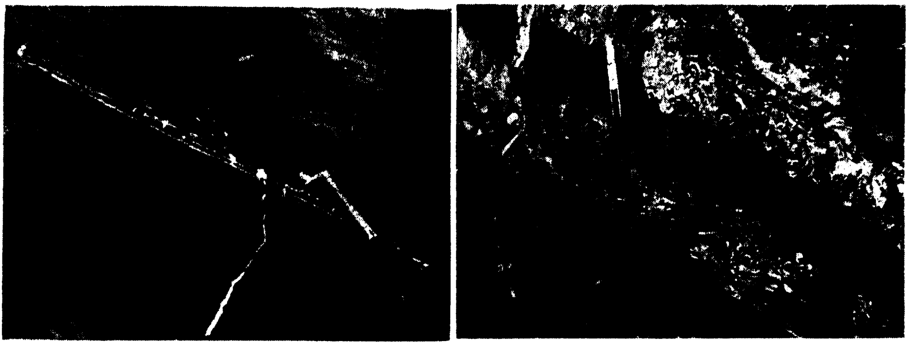
FIG. 2.—Diagrammatic analysis of slate structures (Columbia-Delaware section in northern or "normal" area). *A:* Seventy-five poles of bedding planes. *B:* Schematic diagram of major structural elements. *C:* Two hundred joint poles.

section, projected on a horizontal plane. The most common (modal) strike of the bedding derived from these data is 45°, and the dip is 60°–70° southeast. The axes are horizontal or dip very gently to the northeast. The vertical girdle of points, which passes through the center of the diagram, indicates that the fold axes are $\pm$ horizontal. The concentration of points just northwest of the strike line indicates the predominance of overturning, with the gently dipping southeast limbs exposed over a greater area.

Prior to the development of cleavages, all movements resulting from folding took place along the bedding planes. This movement was in the direction fixed by the intersection of the *ac* plane and the bedding, i.e., in the *a* direction.

The most noticeable result of the folding in the sandy beds is thickening at crests and at troughs of folds. Less common is stretching of a competent horizon on the long limb of a fold so that it becomes attenuated and in some cases has broken across the bed to form a blunt lens. This is an extreme result of stretching in *a* and is not to be confused with boudinage structure,[7, 8] which has no recognizable strike and is supposedly dependent for its distinctive barrel-like cross section on both tension and compression.

As mentioned by Behre,[9] horizons of almost pure calcite up to 3 or 4 inches thick are common and are most noticeable on the southeast limbs of the folds. They have evidently been planes of movement, as they are deeply slickensided in the *a* direction. At places these bedding slips break across at a low angle and become true thrust faults. Extensive movement has resulted in the development of wide ribbons with included angular slate fragments. Associated with the movement in *a*, minor tension joints in *bc* have been opened and then filled somewhat later with quartz (Fig. 3).



A *B*

FIG. 3.—*A*: *bc* tension joints have opened up across calcite horizon ("silver ribbon") and later have been filled with quartz. Columbia-Delaware section. *B*: Shear folding along flow cleavage plane in a wide calcite horizon.

The bedding is intersected by flow

[7] P. J. Holmquist, "On the Relations of the 'Boudinage Structure,'" *Geol. fören. i. Stockholm förhandl.*, Vol. LIII, Part II (1931), pp. 193–208.

[8] T. T. Quirke, "Boudinage and Unusual Structural Phenomenon," *Bull. Geol. Soc. Amer.*, Vol. XLVII (1923), pp. 649–60.

[9] P. 148 of ftn. 1.

cleavage. Because the flow cleavage normally lies in the axial plane of the overturned folds, these intersections may, for all practical purposes, be regarded as parallel to the fold axes (*b*). The pitching of folds results in minor convergences and divergences of the two, but for small angles of pitch these differences are negligible.

South of the dashed line on the map (Fig. 1), fracture cleavage is superimposed on flow cleavage. Here the intersections between bedding and fracture cleavage have been mapped as *b′*. As described below, when viewed in plan, the fracture cleavage cuts all earlier secondary *S* planes at a small angle. For this reason, the intersections with bedding are not so regular as in the northern area.

So far, all folding described has been flexure folding, in which the bedding is the important structural element. As soon as a cleavage develops which transects the bedding, the latter surrenders its active role. From that time on, most movements will take place along the new *S* planes. The bedding is passive. A later stage of the folding illustrates this principle. Shear folding becomes the dominant type immediately upon formation of the cleavage planes. It results from minute movements along the cleavage planes and, in this region at least, simply accentuates the original folds. Such structures have been described by E. Cloos.[10]

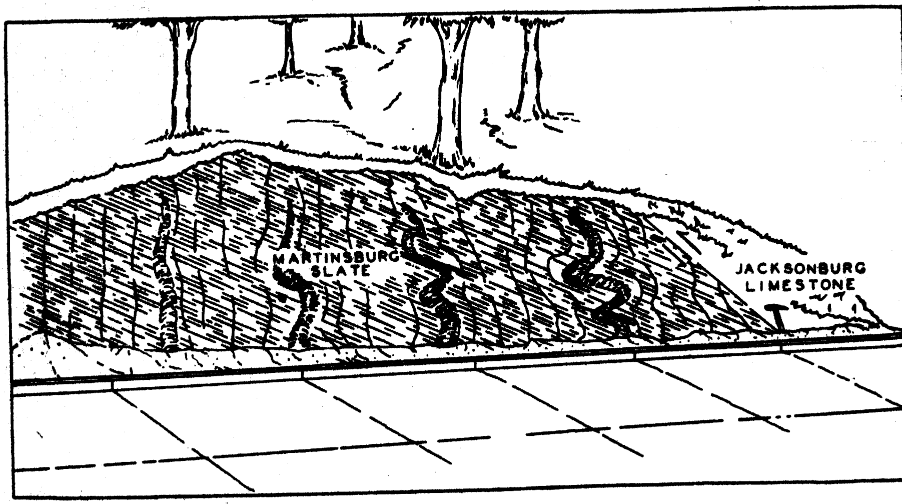


FIG. 4.—Aclinal folding. Sheared S_3 transects bedding and is folded with it. Black bars across folds represent quartz veins.

The latest stage of folding is in the vicinity of the major thrust fault (Fig. 1). The only locality where such folding may be observed is in the road cut on New Jersey Route No. 6 (Belvidere division). Here carbonate lenses have been contorted to a degree of intensity which is inversely proportional to their distance from the major overthrust contact. In this cut the thrust is represented by

[10] "The Application of Recent Structural Methods in the Crystalline Rocks of Maryland," *Md. Geol. Surv.*, Vol. XIII, Part I (1937), pp. 27–105.

Jacksonburg limy shale resting on the Martinsburg with 4–6 inches of gouge marking the contact. The bedding of the slate is generally vertical, with strong folding in the immediate vicinity of the lenses. The two lenses which have been most highly deformed are within 10 feet of the thrust; the last of the series is 125 feet from the contact and is the most gently folded. As shown in Figure 4, the cleavage (S_3) has been folded with the bedding. An apparently unavoidable conclusion is that this local folding has been caused by downward compression exerted by the overriding Jacksonburg on the vertical slate beds. It shows most strongly in the limy lenses because of their plastic character. Comparable structures, with similar interpretation, have been given the name "aclinal folds" by Edward Greenly.[11]

FLOW CLEAVAGE (S_2)

In order that a clear picture of the structural elements and their relations may be built up, it is important that flow and fracture cleavage be recognized as distinct features, although genetically there need not be, and probably is not, any difference between the two. By flow cleavage the author means a cleavage which has developed by rotation, flattening, and growth of mineral grains into approximate parallelism. The use of the term "fracture cleavage" is limited in this paper to a cleavage of the type defined by C. K. Leith[12] as "dependent for its existence on the development of incipient parallel fractures which by subsequent welding or cementation remain planes of weakness." In most cases the parallel fractures appear as minute faults associated with crenulations of the particular S plane which has been deformed. If this purely formal definition were followed, a cleavage plane would have its classification changed from flow cleavage to fracture cleavage as it passed from a shaly to a sandy bed (R. Balk[13]). A reasonable practice seems to be to use the name "flow cleavage" for the type that dominates at any particular exposure and therefore represents the highest degree of cleavage development at that exposure.

For the sake of clarity the slate area as mapped may be divided into a northern, or "normal," area and a southern area. In the first the structures are as described by Behre in Pennsylvania, while to the south they differ radically. The approximate line of demarcation between the two areas is marked by a broken line on Figure 1.

In the northern area, flow cleavage is the dominant secondary structure. Its attitude is extremely constant, striking 40° and dipping 45° southeast. This cleavage is a true axial-plane cleavage, which permeates the entire rock (Fig. 8, *A*). Bedding as a distinct plane of discontinuity has vanished and, except for the massive sandy beds, may be recognized only by color changes dependent on composition. The angle between the bedding and the cleavage may range between 0° and 90° (Fig. 5). As others have noted elsewhere, the angle at which flow cleavage crosses a bed is dependent on the competency of the bed and is always larger in the sandy members.

In the southern part of the slate belt, intricate structures are found involving

[11] "The Geology of Anglesey," *Mem. Geol. Surv. Great Britain* (London, 1919), p. 190.

[12] "Rock Cleavage," *U.S. Geol. Surv. Bull.* 239 (1905), p. 119.

[13] "Structural and Petrological Studies in Dutchess County, New York. I. Geological Structure of Sedimentary Rocks," *Bull. Geol. Soc. Amer.*, Vol. XLVII (1936), p. 706.

fracture cleavage, together with folded flow cleavage and refolded bedding. These structures are described below in more detail. However, it should be noted here that, south of the zone bounding the ordinary structures, flow cleavage becomes progressively more subordinate until, near the thrust contact, it has faded to a relict structure. In this belt, bedding and flow cleavage are most commonly parallel or subparallel.

Movement in the direction of *a* may be noted in the flow cleavage, as well as in the bedding. Evidence of this move-

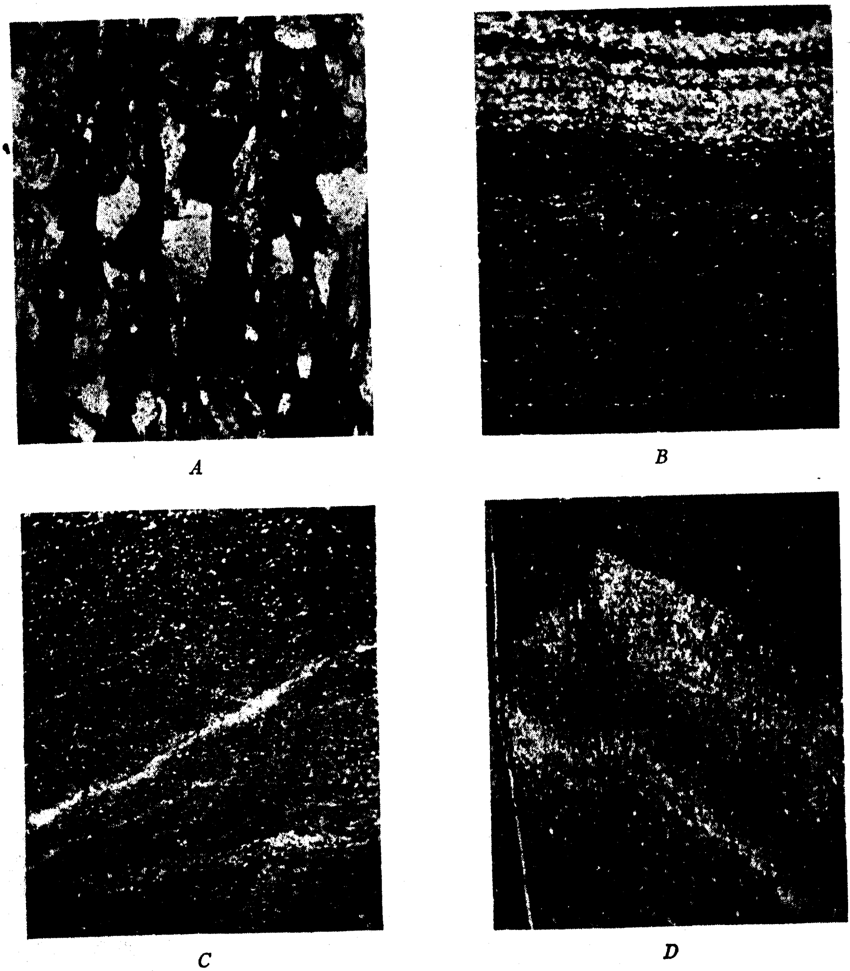


FIG. 5.—*A:* Quartz grains elongated in *a* of flow cleavage. Photomicrograph of Martinsburg slate near Pen Argyl, Pennsylvania, lent by Pennsylvania Geological Survey. *B:* Fracture cleavage dominant. Bedding and flow cleavage essentially parallel. Quartz grains elongated in *a* of flow cleavage. One-quarter mile east of Ramseysburg on road to Hope (sp. 39–65). *C:* Fracture cleavage dipping steeply, flow cleavage gently, to the left. One-half mile southeast of Delaware (sp. 39–78). *D:* Same specimen as Fig. 7, *D*. Relict flow cleavage not visible (sp. 39–74).

ment can be seen very faintly in cleavage planes, expressed by a smearing-out of pyrite flakes into tiny parallel lenses. Other minerals show the same habit but cannot be identified. That this involves true stretching of the rock and not merely slickensiding is borne out by the microscopic evidence, which shows all quartz grains elongated in *a* (Fig. 5, *A*). This direction of elongation is included within the *ac* plane of potential weakness, generally known as the "grain" of slate. The elongation of quartz grains was developed during the formation of the flow cleavage, in the end stages of the folding process. The writer would question recent statements in the literature[14] that elongation of material in the axial plane of a fold normal to the direction of the fold axis is rare or questionable. Grain is a result of this quartz elongation (as well as that of other minerals). Interpretation of this pervasive structure as a tensional effect of the elongation of fold axes fails when it is recognized that the stretching in *a* developed at the same time as the h0l cleavage planes. The capacity of slate to be broken along these *ac* grain surfaces is directly dependent on the development of flow cleavage and the resulting mineral orientation.

FRACTURE CLEAVAGE (S_3)

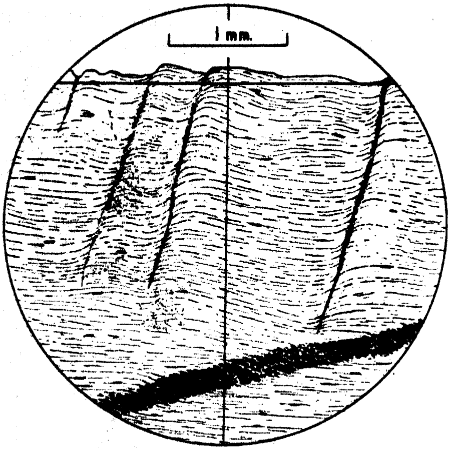
In the belt of "normal" structures (northern area), fracture cleavage seems to be absent. The structure mapped by Behre as fracture (false) cleavage appears as small jointlike fissures, which give a wavy, crinkled effect to the flow cleavage (Fig. 7, *C*). In appearance it is similar to structures usually identified as fracture cleavage. It strikes parallel to the flow cleavage and dips 90° from it. Since it is found most commonly where thin shale beds are sheared between massive sandy horizons, Behre[15] ascribed its origin to such movement. It is now apparent that the origin is somewhat more complex (Fig. 6, *A* and *B*). The writer believes that the planes were formed originally as a result of tension parallel to *a* in the cleavage planes. Microscopic study shows that they are actually tiny gashes paralleling *bc* which peter out no more than 3 mm. from their surface of origin. The action of the bedding movement (Movement 1, Fig. 6, *B*) was secondary and resulted in slipping and flattening of the flow-cleavage planes (Movement 2, Fig. 6, *B*) by rotation between the massive sandstone layers. This caused an antithetic movement along the *bc* planes, which folded and dragged the flow-cleavage planes (Movement 3, Fig. 6, *B*). This structure has been noted only on the gently dipping southeastern limbs of the folds.

As one proceeds from north to south, one encounters in the vicinity of Delaware a fracture cleavage which is later than the bedding and the flow cleavage of the region as a whole. The dividing zone between the "normal" area and that in which this cleavage predominates parallels the regional strike and is so sharp that it has been represented on the inset map as a broken line. In a few localities this transition zone widens to about half a mile. From here on southward to the major overthrust, the dominant structure is a well-developed fracture cleavage which parallels the axial planes of flow-cleavage folds. This association indicates that it is genetically related to the folding. Locally, especially in the vicinity of quartz reefs, the contortion of S_2 is very strong (Fig. 8, *B*).

[14] E. B. Knopf, "Structural Petrology," *Geol. Soc. Amer. Mem. VI* (1938), p. 152.

[15] P. 36 of ftn. 1.

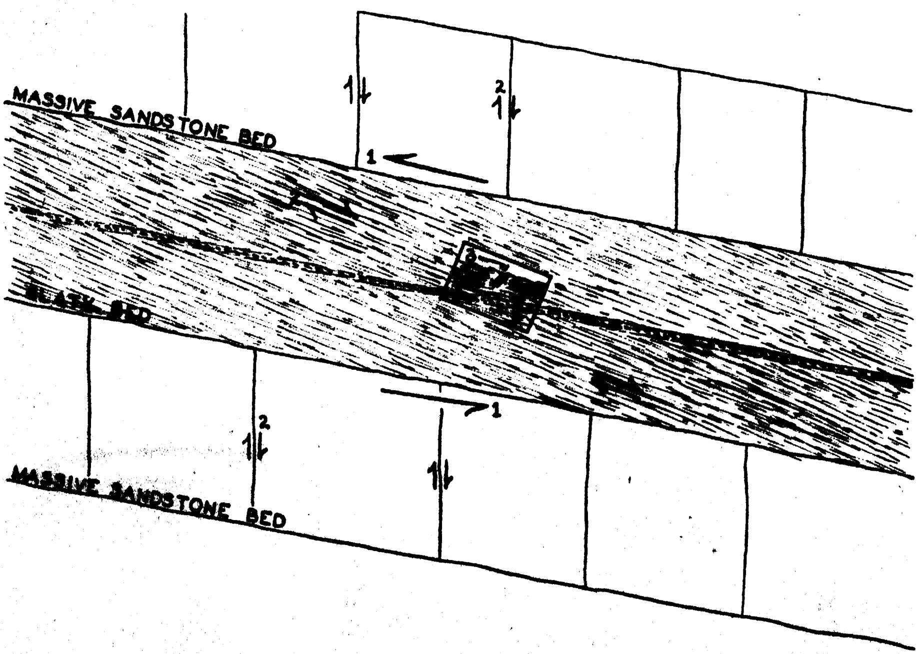
Elsewhere the flow cleavage is found at a small angle to, or parallel with, the bedding (Figs. 5, *B* and 7, *B*).



A

Relations of the three *S* planes to one another are particularly well exhibited in the Delaware, Lackawanna, and Western Railroad cut at Ramseysburg (Fig. 8, *B*) and a few hundred feet east of that cut on the road to Hope. At the latter exposure, numerous small, steep thrust faults have formed parallel to the fracture cleavage and then have broken through at anticlinal crests. Generally, where this late cleavage was formed, subsequent movement along it or along paralleling faults indicates antithetic rotation[16] to the northwest. Rotation of fracture-cleavage planes is indicated by drag of the earlier *S* planes and suggests flattening of S_3 as a result of continued pressure from the southeast.

[16] "Structure Elements of Domes," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. XX (1936), p. 61.



B

FIG. 6.—*A:* Camera lucida drawing of rotated *bc* tension joints. *B:* Diagrammatic interpretation of structure shown in *A*. Rectangle gives location of thin section. Not to scale.

Slipping of the planes past one another has produced strong slickensiding on every fracture-cleavage surface. It is much more easily visible than the stretching along *a* in the flow cleavage, although it is not so pervasive. Consequently, it has had no effect on the internal structure, except possibly in a few localities where deformation was stronger.

Over most of the area these features of the fracture cleavage persist to the overthrust contact. However, at some localities marked on the map as "probable S_3," its appearance becomes so similar to normal flow cleavage that it was originally mapped as such (Fig. 8, *C*). Nevertheless, the writer has become convinced that it is the same fracture cleavage but that the slate has undergone intense deformation. As stated above, the original flow cleavage occurs at these exposures as a relict structure. This may be seen in the railroad cut at Manunka Chunk. Figure 7, *D*, is a good example of the mutual relations of the two cleavages

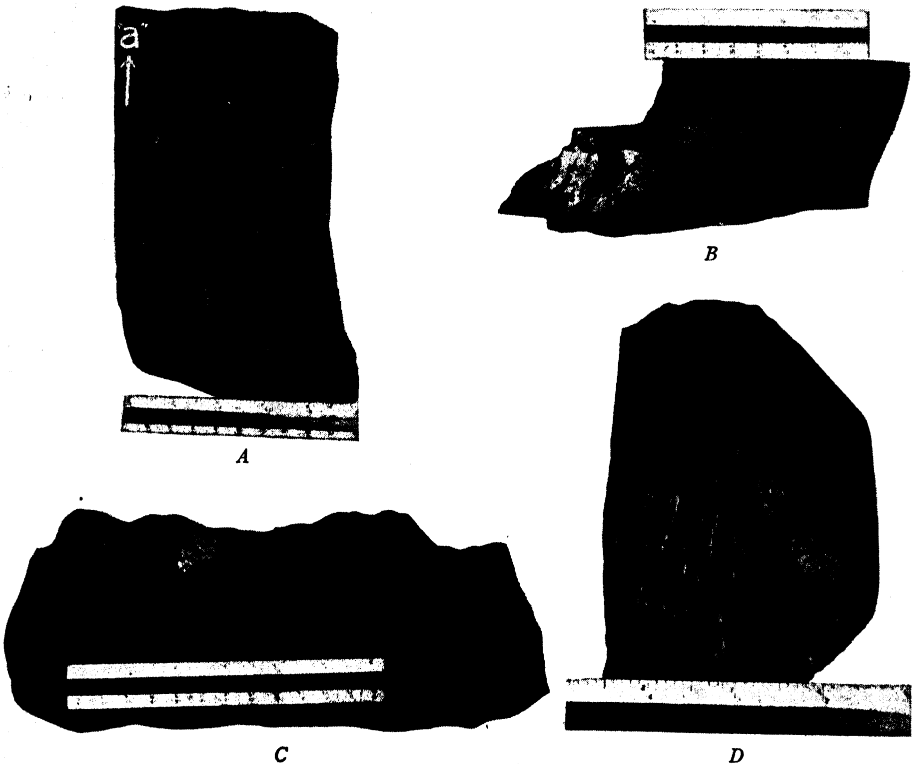


FIG. 7.—*A:* Fossils in Jacksonburg limestone pulled out by movement in *a* along bedding. Rock splits parallel to grain (*ac*). Near thrust contact, $\frac{3}{4}$ mile south of Swayse's Mills. *B:* Fracture cleavage dominant. Bedding and flow cleavage essentially parallel. One-quarter mile east of Ramseysburg on road to Hope (sp. 39–65). *C:* *bc* joints developed normal to *a* of flow cleavage. Columbia-Delaware section. *D:* Sheared fracture cleavage. Bedding dips away and to the right of the observer. Relict flow cleavage dips steeply to the left. Pennsylvania R.R. cut—Manunka Chunk (sp. 39–74).

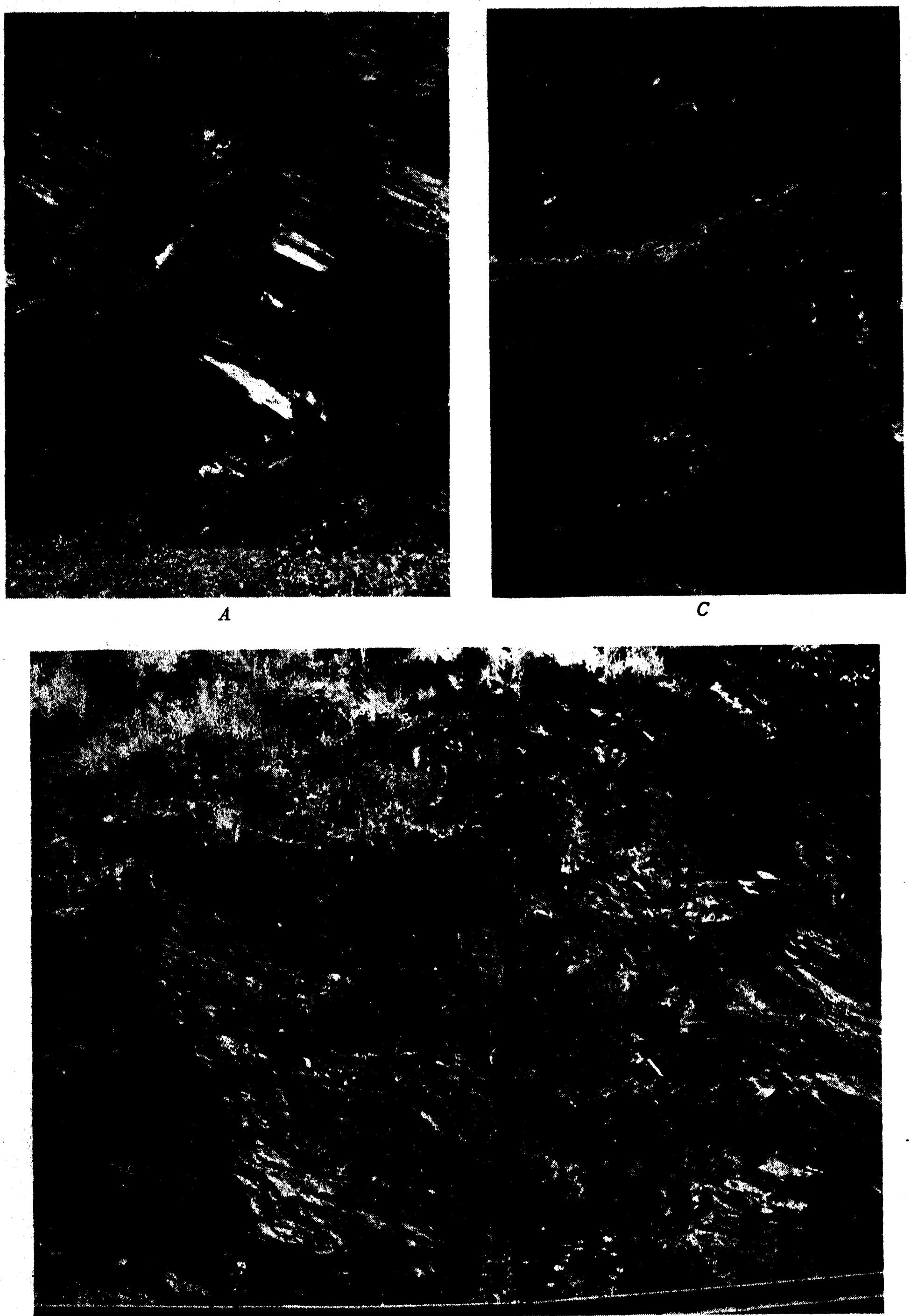


FIG. 8.—*A:* Axial-plane flow cleavage. Columbia-Delaware section. *B:* Bedding roughly vertical. Flow cleavage gently dipping at left and extremely folded on right. Fracture cleavage parallels axial planes of flow-

and of the bedding. In thin section (Fig. 5, *D*), flow cleavage is not visible except upon insertion of the gypsum plate, when a faint structure may be seen crossing both fracture cleavage and bedding at an angle. The fracture-cleavage plane has lost its typical microscopic appearance and has developed into a structure which seems to be transitional between fracture cleavage and flow cleavage. The uniform elongation of quartz grains in S_2, observed farther north, has disappeared. The author has interpreted this phase as the result of continued and stronger pressures which have started to develop mineral reorientation and a resultant younger-generation flow cleavage along the fracture-cleavage planes.

Since the field work for this study was completed, a paper by W. J. Mead[17] has appeared, in which he sets up a threefold division for the secondary cleavages. Flow cleavage and fracture cleavage are two of the divisions. The third is "shear cleavage." Of this latter structure Mead says:

> This type of cleavage consists of roughly parallel, closely spaced surfaces of shear displacement on which platy minerals may have developed and into which they may have been dragged .... when the spacing is unusually close, shear cleavage may simulate and be easily confused with flow cleavage.

The writer believes that shear cleavage can be a transitional stage between flow and fracture cleavage. This is discussed below in more detail.

A genetic correlation of this regional fracture cleavage with the major overthrust, of which Jenny Jump Mountain is a part, seems to be an obvious conclusion. The main criteria on which this correlation is based are: (1) the bending of the fracture-cleavage strike opposite that part of the overthrust which seems to have advanced farthest, (2) the gradual increase in intensity of deformation toward the fault, and (3) the fact that the dip of the cleavage progressively flattens from north to south. All suggest the gradual building-up of stress from the southeast with antithetic rotation of the *S* planes, until, in the final stage, the weaker rocks were overridden by the older gneisses and limestones.

The sharp division between the two structure types in the slate is peculiar. The sudden change from fracture cleavage to flow cleavage northward suggests the possibility of a thrust entirely within the slate, although no such structure was observed. The author has refrained from adding another hypothetical fault to the many that have been postulated in the Appalachian province.

JOINTS

Three well-developed sets of joints cut the slate and its structures throughout the northern, or normal, part of the slate belt. Two hundred joints were measured along the Delaware River between Delaware and Columbia and their poles plotted on an equal-area net (Fig. 2, *C*). Comparison of this diagram with the block diagram (Fig. 2, *B*) illustrates their relation to the axes of deformation.

The submaximum in the first and third quadrants of Figure 2, *C*, represents vertical joints which are exactly at 90° to the strike of the fold axes. They are parallel to the grain of the *ac* direction in the rock and are thus in the proper geometric position for cross-joints. Grain of slate is such a pervasive plane of weakness that in any cut or excavation large vertical faces develop parallel to it. This is the sole joint direction

[17] "Folding Rocks Flowage and Foliate Structures," *Jour. Geol.*, Vol. XLVIII (1940), pp. 1007–21.

found constantly throughout the slate area, regardless of the cleavage type which exists. These joints appear most commonly where diagonal joints are rare. The roughhewn character and position of these cross-joints would seem to indicate that they are natural partings along the slate grain. The unevenness of the *ac* joints is explained by the fact that eventual breaking is not along one plane but along many roughly parallel planes, all including and being guided by the direction of quartz elongation (*a*). It is uncertain whether the actual fractures resulted from tension caused by elongation parallel to the *b* axis during folding or by continued pressure in a northwesterly direction after formation of grain. In the latter case, the *ac* joints might be thought of as incipient tear faults.[18]

The sharpest and smoothest joints are inclined to the *b* axis of folding (Fig. 2, *C*) and are probably shear joints. They are commonly coated with calcite films.

Strike joints (Fig. 2, *C*) have a very regular strike. However, it is common for the dip to swing from northwest to southeast or vice versa within a single joint. These surfaces are not so smooth as are the diagonal joints.

All three sets are best developed when their strike and dip are nearest the position indicated by the maximum on the diagrams.

FAULTS

The major fault affecting the slate belt is the thrust fault which bounds it on the south. Bayley and Kümmel[19] have interpreted it as a flat overthrust. The areal map of Northampton County, Pennsylvania,[20] shows no fault extending across the Delaware River into Pennsylvania.

Field evidence indicates that the thrust fault does exist, but it cannot be stated with certainty that it is a flat overthrust.

At the exposure on New Jersey Highway No. 6, from which the folded carbonate lenses are described, Jacksonburg limestone was found resting on Martinsburg slate with a foot or less of gouge between the two. This exposure is only ½ mile east of Northampton County. The fault dips 40° southeast. On the evidence of this exposure, the author has drawn the fault line on his map ¼ mile north of where it appears on the New Jersey State Geological Map (1933).

On the southwest end of Jenny Jump Mountain, Kittatinny limestone was found below pre-Cambrian gneiss. The contact was not seen. However, the limestone has been completely silicified in a zone at least 5 feet thick and has been sheared into flat-lying (5°–15°) folia.

In a new highway cut, ½ mile south of Swayze's Mills (2 miles southwest of Hope), the Jacksonburg cement rock is found in a highly contorted and shattered condition. Folding is intense, and stretching and lensing of sandy beds in *a* are common. A slab of rock taken from this locality shows fossils elongated parallel to *a* on the bedding planes (Fig. 7, *A*). The cement rock appears to be above the slate, but the actual contact was not seen. The author drew the fault line here farther north than it is drawn

[18] T. S. Lovering, "Field Evidence To Distinguish Overthrusting from Underthrusting," *Jour. Geol.*, Vol. XL (1932), p. 651.

[19] W. S. Bayley, H. B. Kümmel, and R. D. Salisbury, "Raritan Folio," *U.S. Geol. Surv. Folio, 191* (1914), p. 149.

[20] B. L. Miller and D. W. Fraser, "Northampton County, Pennsylvania," *Pa. Geol. Surv. Bull. C48* (4th ser., 1939), Pl. I.

on the state map, because of this exposure.

The attitude of fold axes around an outlier serves as a clue as to whether the rock mass is a true klippe or simply an anticlinal core. In the latter case, fold axes pitch outward in the surrounding rock. Not enough observations could be made at this locality. Nevertheless, as far as could be determined, fold axes in the slate pitch inward toward the limestone outlier. Since the limestone is the older rock, this synclinal structure indicates that there must be a fault separating the two.

Faults within the slate belt appear to be confined to renewed movement along zones of earlier fracture, such as the thrusting along fracture-cleavage planes near Ramseysburg. In places, faults have broken across the bedding planes as the dip changes near the crest of a fold. This is simply stronger movement of the same type that caused the common slickensiding in the *a* direction in the bedding planes. It is seen more often where flow cleavage and bedding are nearly parallel. In at least one case, rotation of the intermediate block has occurred between two slightly convergent bedding-plane faults. Feather joints may sometimes be noted branching off from the main plane of movement.

FABRIC

Fabric diagrams of typical specimens of the slate tend to corroborate the separation of the cleavage in the field.

Figure 9, *B*, is a diagram of two hundred quartz axes from a sandy layer in the slate of the "normal" area. This specimen (39–31) was collected along New Jersey Highway No. 8, $3\frac{1}{4}$ miles south of Columbia. The attitude of the flow-cleavage plane (S_2) has been indicated. There is no visible fracture cleavage. The concentric circles represent those circles passing through the theoretical quartz tectonite maximums.[21] There is some elongation of the individual quartz grains in *a* of the flow cleavage, but this is not so marked as in the more shaly layers. The quartz grains average 0.05 mm. in diameter.

Coincidence of actual point maximums with those theoretically possible is the exception rather than the rule. However, rotation about *b* is indicated, inasmuch as all the more important maximums and submaximums fall on, or very near, some of the maximum circles. The maximum of 4 per cent at *a* is most easily identified.

It corresponds to Maximum I, which has been interpreted[22] as a result of quartz breaking into needles parallel to its *c* axis and orientation of the needles parallel to fabric axis *a*. A maximum of equal importance lies in the *ac* plane 56° ± from *a*. Lying, as it does, midway between the theoretical Maximums II and V (Fig. 9, *A*), its interpretation is questionable. There is no field evidence to support the hypothesis that it represents Maximum I of another cleavage plane. It will fall roughly on the VI circle if *a* is taken as an axis of rotation; but in this locality there is no evidence whatever to suggest that such was the case. Finally, it may be taken simply as a point maximum falling on the *ac* girdle I-II-V. Whatever the allocation, the author does not feel capable of giving an adequate interpretation.

Submaximums of 3 per cent each lie on the IV, VI, and III circles. The actual

[21] H. W. Fairbairn, *Structural Petrology of Deformed Rocks* (1942), p. 68.

[22] David Griggs and J. R. Bell, "Experiments Bearing on the Orientation of Quartz in Deformed Rocks," *Bull. Geol. Soc. Amer.*, Vol. XLIX (1938), p. 1743.

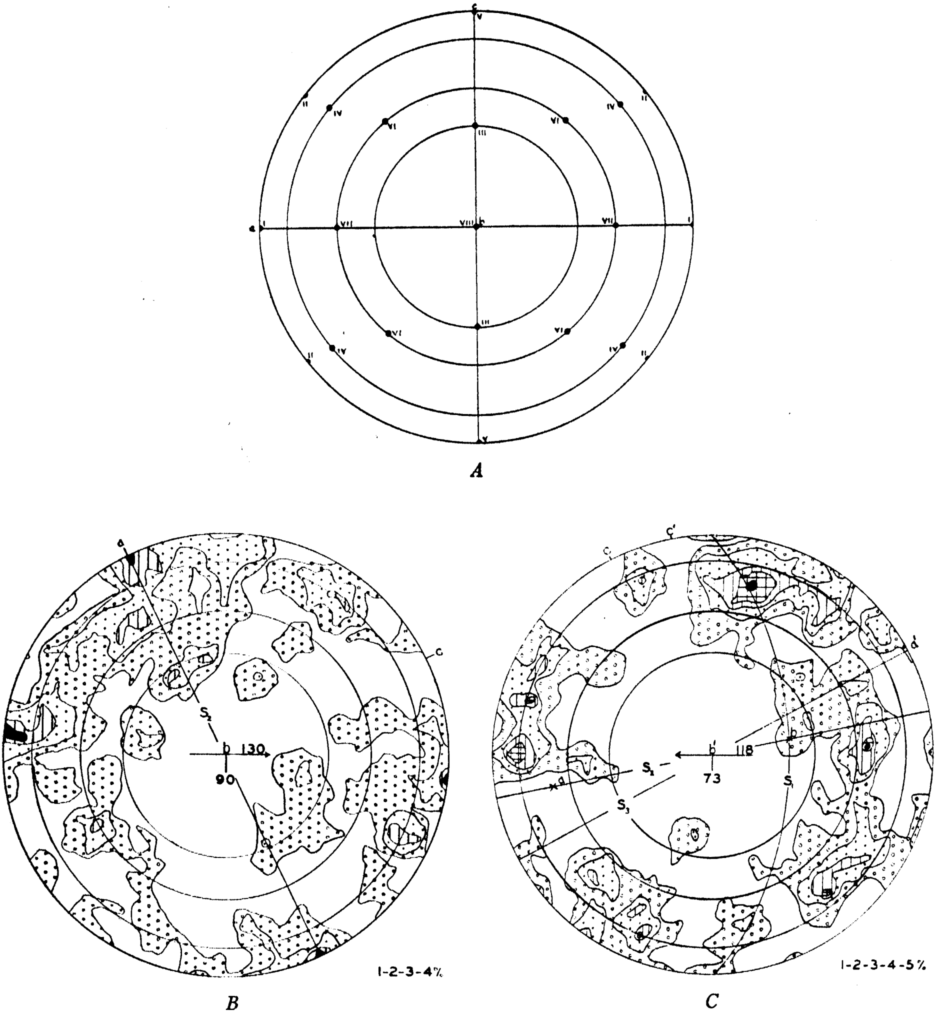


FIG. 9.—*A:* Theoretical quartz tectonite maxima after H. W. Fairbairn in *Structural Petrology of Deformed Rocks* (Cambridge, Mass.: Addison-Wesley, 1942). Drawing reproduced by permission of the author. *B:* Fabric diagram with optic axes of 200 quartz grains in sp. 39–31. *C:* Fabric diagram with optic axes of 200 quartz grains in sp. 39–74.

and theoretical maximums coincide in only one case.

Figure 9, *C* (39–74), is a quartz diagram (two hundred axes) from the slate of the southern area, in which the flow cleavage appears as a relict structure. The specimen was collected along the Belvidere branch of the Pennsylvania Railroad, 1¼ miles south of the junction with the Delaware, Lackawanna, and Western Railroad at Manunka Chunk. All three *S* planes have been drawn into the diagram. S_2 was measured indirectly by determining its intersections with two joint surfaces; *b* was taken as the intersection of S_1 and S_2; and b' as the intersection of S_2 and S_3. The braided appearance of the rock in thin section (Fig. 5, *D*) results from the intersection of the two cleavages. The quartz grains average 0.035 mm. in diameter.

A study of the maximums indicates that b' has been of greater and more recent importance as an axis of rotation than has *b*. With b' as an axis of rotation, all maximums greater than 3 per cent fall either on the IV circle or in the zone between the IV and the VI circles. This type of orientation has been described by H. W. Fairbairn[23] in folded quartzites. If the diagram is rotated so that *b* is at the center, the following arrangement of maximums and submaximums may be seen—six between circles IV and VI and one within circle III. Further, these maximums are not arranged in girdles so completely as in the first case. It is possible that the 4 per cent submaximum nearest fabric axis *a* is the Maximum I already observed as characteristic of the flow cleavage (Fig. 8, *B*).

For these reasons, it appears that the original orientation about *b* has been destroyed and that a later one, developed by slipping and antithetic rotation along S_3, has been superposed. If this type of movement is the same as in the development of S_2, then the process has not gone so far. Further stretching of the fabric in a', just as the rock was originally stretched in *a*, should result in the development of another Maximum I.

SUMMARY AND CONCLUSIONS

The structures of the Paleozoic rocks indicate that they have been subjected to at least two periods of deformation. These structures might well be explained as the result of two peaks in the stress cycle of one period, were it not for the evidence of surrounding areas. Previous investigators (Behre, 1925; Miller, 1926; Stose, 1930) have shown that post-Ordovician, pre-Silurian folding took place. This has been correlated with the Taconic disturbance. The entire region was later affected by the Appalachian Revolution.

The flow cleavage of the Martinsburg formation may be dated as Taconic, since it parallels the axial planes of the folds of that disturbance. The bedding slip which accompanied the earlier stages of folding was superseded by slipping along cleavage surfaces. By this shearing movement, quartz orientation was developed which is believed to be typical Maximum I, in which both the optic axis and the major dimensional axis of quartz grains were aligned in the *a* direction. This pattern is associated with *ac* girdles resulting from folding, in which $b = B$. The external orientation forms the "grain" of the slate quarryman and is shown on the cleavage surfaces as a faint lineation.

The Appalachian orogeny is repre-

[23] "Hypotheses of Quartz Orientation in Tectonites," *Bull. Geol. Soc. Amer.*, Vol. L (1939), pp. 1475–92.

sented in this region by thrust faults and by a well-developed fracture cleavage. The Cambro-Ordovician and pre-Cambrian rocks exposed on Jenny Jump Mountain are, according to Bayley and Kümmel, underlain by a flat thrust fault. A reverse fault is present, but a flat overthrust is not supported directly by the field relations. At the only point where it could be observed, the fault plane dipped 40° southeast. Elsewhere all the evidence points indirectly to overthrusting. The flatly sheared silicified limestone beneath the gneiss of the Jenny Jump Mountain, the greatly stretched and broken formations of the footwall, and the isolated outlying limestone masses—all are characteristic of a thrust fault of considerable magnitude.

Although thrusting was the culmination of the process, the stresses that preceded it also had a strong effect upon the slate. These stresses, probably acting from the southeast (although with some small deviation from those of the Taconic orogeny), folded the flow cleavage and the bedding with it. Over much of the area, however, flow cleavage now parallels the bedding, which, especially in the massive sandy horizons, appears only slightly disturbed. Very similar relations exist between the two in the Mona complex in Anglesey. Edward Greenly[24] has explained it by isoclinal folding of flow cleavage between the thick uncleaved sandy layers. A secondary effect of the thrusting was the formation of fracture cleavage in the Martinsburg. This is seen up to a maximum distance of 3 miles north of the present fault trace. It bears the same relation to the flow cleavage as that structure bears to the bedding. The writer believes that this secondary cleavage was developed by the thrusting and overriding of the older rocks. Rotating and flattening of the cleavage layers by the same agent is evidenced by progressive flattening of their dip southward, as well as by the gradual change in character of the cleavage. Thus the cleavage was developed by shearing until it was well on the way to becoming a second flow cleavage. The progressive obliteration of the first flow cleavage was a necessary accompaniment. The degree to which the metamorphosis has advanced is clearly shown by the fabric analysis of the slate close to the overthrust, in which it appears that b' (the intersection of S_2 and S_3) = B. However, the flow-cleavage Maximum I has not developed. Evidently, considerable shearing under long-continued stresses is necessary for its formation. Fracture cleavage, commonly considered to be a minor structural feature, often remains unexplained or is lumped together with the other associated phenomena of flow cleavage. It is the contention of this paper that this is an area in which it can be definitely mapped as a regional structure and assigned to a specific cause—major thrust faulting. The opportunity of tracing the development of a cleavage as it is affected by stresses of progressively increasing intensity is of particular interest.

ACKNOWLEDGMENTS.—Ernst Cloos has been particularly helpful during the course of the work. The author also wishes to acknowledge the friendly criticism and advice of the late B. L. Miller and Walter H. Bucher. Mark H. Secrist, H. L. Alling, and Earl Ingerson kindly lent certain scientific instruments. The original of Figure 5, *A*, was lent by C. H. Behre, Jr. William Saunders, of the University of Rochester, assisted the author in the field during the 1939 season. C. L. McNulty, of Syracuse University, drew Figure 4.

[24] "Foliation and Its Relation to Folding in the Mona Complex at Rhoscolyn (Anglesey)," *Quart. Jour. Geol. Soc.*, Vol. LXXXVI (1930), p. 171.

PRELIMINARY NOTE ON VOLCANIC ERUPTIONS IN THE GOROPU MOUNTAINS, SOUTHEASTERN PAPUA, DURING THE PERIOD DECEMBER, 1943, TO AUGUST, 1944

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ABSTRACT

The phenomena and effects of new volcanic vents of the explosive type in the Goropu Mountains, Owen Stanley Ranges, Papua, are described on a basis of reports made by local observers. Petrological examination of lapilli from the vents indicates that an andesitic volcano has broken through ultrabasic rocks forming part of the Owen Stanley Ranges.

INTRODUCTION

Explosive volcanic activity has occurred since December, 1943, and is continuing spasmodically in the foothills of the Goropu Mountains, Papua, where previously no volcanic activity had been reported. Intervals between the first four recorded eruptions were 7, 23, and $5\frac{1}{2}$ weeks, respectively. The Goropu Mountains lie inland from Collingwood Bay (Fig. 1), 130 miles east of Port Moresby. The active vents, which are 40 miles south-southwest of Tufi government and mission station, broke through pre-Tertiary rocks, considered by E. R. Stanley[1] as Paleozoic or pre-Cambrian.

Although no volcanic activity had been reported previously from this particular locality, it is possible, since Stanley[2] has recorded hot springs and solfataric activity 65 miles to the west-northwest, that minor thermal activity may also have occurred in this unexplored area. It is unlikely, however, that violent explosive phenomena of the kind dealt with herein occurred within human memory, because of the relatively close proximity of mission and government stations to the active area, from which no previous reports of explosive vulcanicity have emanated.

REVIEW OF EYEWITNESS REPORTS

Prior to the explosive eruptions here described, columns of steam and ash from four volcanic vents were observed in October and November, 1943, and earth tremors had occurred during the previous two years, sometimes at the rate of two or three a day.

The first recorded eruption, that of December 27, 1943, ejected a crater-cloud of ash and steam to an estimated height of 15,000 feet. An electrical storm accompanied the eruption. No tremors or noises were reported from Tufi Station in connection with this eruption. Lapilli, carbonized wood fragments, and volcanic ash landed in native gardens at Iu-ai-u (U-ai-u), a coastal village 16 miles from the active vents. Fine ash and dust were thickly spread out on an 8-mile radius around the vents; mud rains and sulphurous vapors were recorded. Layers of white dust covered trees some distance from the vents. Bird life and leeches had vacated the area, but larger game was still abundant. Nearer the vents the dust layers were so thick that

[1] *The Geology of Papua* (Melbourne, 1923).

[2] "Geological Expedition across the Owen Stanley Range, 1916," *Ann. Rept., Papua, 1917–18* (1919).

the branches of trees were stripped off; all animal life had disappeared from the devastated region.

Ground patrols sent out by the district officer of the Australian Military Administration at Tufi noted that about 2 miles west of the vents there occurred in the devasted area two sheer-sided depressions, 50 feet deep and 100 feet across, which had stony floors but were waterless. In one of these chasms occurred a still further sunken area about 80 feet across and 6 feet deep. Its recent character was indicated by depths of dust greater than those occurring in the immediate neighborhood and by the uprooting of trees in the vicinity; no distinct crater could be discerned. Apparently, the disturbance had been of only sufficient strength to force dust up through the stony floor of the depressed area. Two larger, similar chasms were noted west of Wai-oa Creek, close to the area of the active vents. (Wai-oa Creek is a tributary of the drainage system, which enters the sea between Ganjiga and Ui-aku, as shown in Fig. 1). One of the chasms possessed a rim, 12 feet high and 60 feet long, occurring at intervals along either side of the chasm.

Mud rains, which fell during the approach of patrols to the active vents, covered the ground with 2 inches of mud. On the slopes of the Goropu Mountains, only the largest trees were left standing; they had been stripped of branches, and the trunks on the northern side of the vents were pitted right up to the top. All secondary plant growth had been broken down and covered with volcanic mud. This mud had an oily appearance, and its surface reflected trees that were still standing.

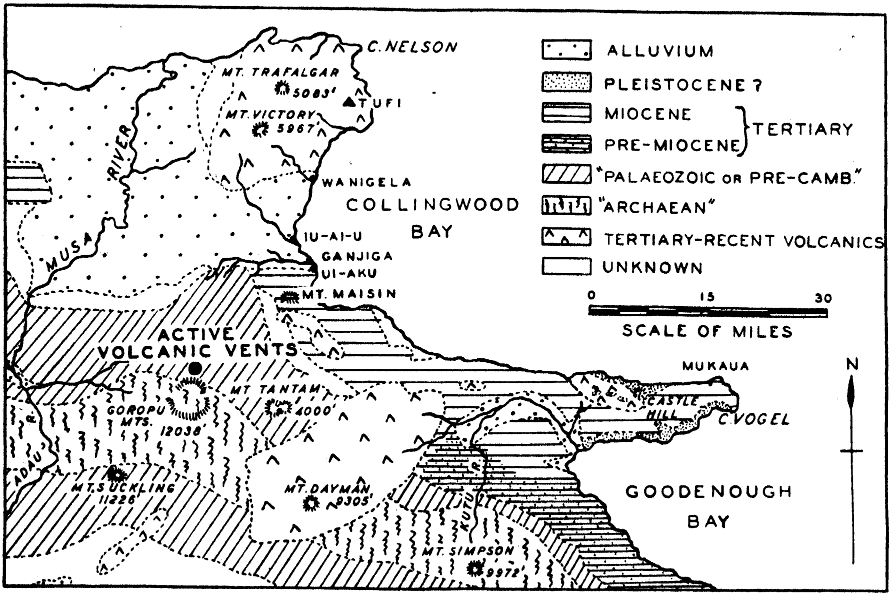

FIG. 1.—Geological map of the Collingwood Bay–Goodenough Bay area, showing site of the active volcanic vents. (Geology after E. R. Stanley, 1923; localities after W. M. Strong, 1916.)

In the center of the region of activity,

one crater with sheer walls was estimated as 90 feet across and 60 feet deep. It was uncertain whether the bottom was covered with mud or solid material; sulphurous vapors were strong around this crater. Near by were two small craters in which the only sign of activity was a slight bubbling of the mud, and below these was an area of mud about three acres in extent, which emitted a white vapor. On a near-by ridge two large active craters gave off dense, brownish-colored steam and ash; stones were being thrown up in their vents. The heights of the cones around the craters were not estimated; but from the aerial photograph (Fig. 2) it can be seen that, even at later stages of eruption, they are relatively insignificant.

Crater-clouds persisted in the volcanic area for several weeks, and at approximately 8:00 P.M. on February 13, 1944, a further, but less severe, eruption than that of December, 1943, was observed from Wanigela, where an earth tremor was felt and explosions were heard coming from the vicinity of the active region. Figure 2, an aerial photograph taken on the following day from about 500–750 feet above the ground, shows a phase of this eruption. No stones or débris landed in the coastal villages of Iu-ai-u, Ui-aku or Ganjiga on this occasion, but some landed in the inland villages of Bonando and Kokoe, respectively 4 and 7 miles west from the coast and about 12 miles north-northeast of the active vents. The area of ash and dust deposits around the vents was considerably enlarged, extending up the slopes of the Goropu Moun-

FIG. 2.—Active vents on the northern flanks of the Goropu Mountains, about 130 miles east of Port Moresby, Papua. Eruption of February 14, 1944. Note craterlet on flanks of cone in foreground, and symmetrical outline of main crater. (Department of Information photograph.)

tains and increasing the area of devastation in the tropical jungle to at least 20 square miles. No further vents beyond the original four were observed.

These earlier eruptions of the Goropu volcanic vents were evidently directional, as indicated by the pitting of the trunks of trees on the northern side of the vents and by the fact that lapilli were discharged to the north-northeast, landing at the villages of Iu-ai-u, Ui-aku, Ganjiga, Bonando, and Kokoe.

Dust from the eruption of February 13, 1944, was swept in a westerly direction by high-altitude air currents, resulting in the enveloping of the Coral Sea and Port Moresby (130 miles away to the west) in a thick pall of dust on February 14, 1944.

War-correspondent observers from a plane, which flew over the vents on February 14, reported volcanic dust hanging out in thin layers from stratus clouds and stretching for miles out to sea and up into the mountains, where it concentrated along the valleys. The heat from one of the vents could be felt at heights of 500 feet above it; at lower levels the heat was unbearable, the vapors from the crater were nauseating and had a strong sulphurous odor. What appeared like lava streams were reported passing through the brown mud around the vent, but no lava flows have yet been confirmed by ground patrols. The observed phenomena may have been hot or cold avalanches.[3] The crater appeared from the air like "an oversize bomb crater," largely masked by steam; in its center was a dull red glow, but no apparent lava stream issued from the vent itself. A great, dazzling-white pillar of steam rose some 2,000 feet above the crater.

[3] F. A. Perret, "The Vesuvius Eruption of 1906," *Carnegie Inst. Wash. Pub. No. 339* (1924), p. 49.

Later observations, made early in March, 1944, along the course of the Ui-aku Creek, south of Mount Maisin (Fig. 1), indicated that the Ui-aku Creek carried unusually large volumes of water, highly charged with mud, while considerable amounts of silt with large blocks of vesicular rock had been deposited along its banks. All of the mud was being brought down by a branch of Ui-aku Creek from the area of the volcanic vents.

Numerous small, newly developed streams, which flowed at random over the surface, were also charged with silt and vesicular rock. They obviously had their origin principally in the mud rains formed by the condensation of the discharged vapors on dust particles, and probably represent the initiation of a new local drainage system in place of stretches of Wai-oa Creek, reported to have dried up in parts since the inception of volcanic activity. Dislocation of the former drainage system is also indicated nearer the center of the devastated area; the valley of a large creek that originally flowed through flat, gradually sloping country covered with dense jungle growth is now represented by a ridge, narrow below, and widening to half-a-mile or so across near the craters. This ridge is cut by a creek flowing partly into Ui-aku Creek and partly into its former bed near Mount Maisin. The ridge consists of "nothing but baked earth, reddish in color and with a very loose crumb structure." It probably represents a volcanic mudflow of the type known as a *lahar* in Java,[4] where the so-called mud is a mixture of water and ash containing blocks and fragments of rock of various sizes.

White vapors (principally steam),

[4] L. M. R. Rutten, "Voordrachten over der Geologie van Nederlandsch Oost-Indie," *Den Haag* (1927), pp. 149–54.

which rose through cracks 6 inches to several feet long in the ground around the active vents, were sufficiently hot to boil water, while stones on the surface were too hot to handle.

The vents were still pouring forth fumes at the end of April, 1944, three of them continuously and one spasmodically.

At 8:45 A.M. on July 23, 1944, there was a further explosive eruption of the Goropu craters, dust again being strewn over an extensive area, increasing the region of devastation to 30 square miles. All minor vents had been sealed up, and the main crater, now 500 yards across, had commenced to build up its cone with greater rapidity. Blocks of vesicular rock weighing up to 2 pounds were found at Wo-Wo Gap, 15 to 20 miles distant.

On August 31, 1944, dust from a later eruption fell on Port Moresby.

PETROLOGY OF THE EJECTED MATERIALS

Approximately two dozen samples of lapilli and three ejected pebbles were submitted for investigation at the Melbourne University geology department. The lapilli were collected from near Iu-ai-u village, 16 miles from the center of the eruption. Eight samples were employed in the petrological investigations and six in the chemical analysis (Table 1).

Macroscopic investigation shows that the lapilli vary in size from $1 \times \frac{1}{2} \times \frac{5}{8}$ inch to $1\frac{3}{4} \times 1\frac{1}{2} \times \frac{5}{8}$ inches. The lapilli are of irregular shape (Fig. 3, *A–I*), their color is light gray, their texture vesicular, although the number of vesicles varies in different specimens. Polished surfaces show darker colored minerals, mainly up to 1 mm. long, set in the light-gray matrix. A few dark crystals up to 6 mm. in length were isolated from parts of the matrix.

Microscopic examination emphasizes the vesicular character and porphyritic texture of the rock, while also revealing a fluidal arrangement of many of the

TABLE 1

	1	2	3
SiO_2	55.83	54.56	54.14
Al_2O_3	16.23	16.49	16.42
Fe_2O_3	nil.	1.02	1.69
FeO	4.13	5.65	5.26
MgO	7.91	8.57	8.44
CaO	7.87	7.95	8.05
Na_2O	2.30	2.07	2.20
K_2O	3.80	3.35	3.34
H_2O+	0.67	0.15	0.56
H_2O-	0.34	....	....
CO_2	n.d.	....	....
TiO_2	1.14	1.10	1.23
P_2O_5	n.d.	....	....
MnO	0.11	tr.	tr.
Total	100.33	100.91	101.33

NORMS

	1	2	3
Q	3.00	....	....
Or	22.24	20.02	20.02
Ab	19.39	17.29	18.34
An	22.80	25.85	25.02
di	12.95	10.87	11.98
hy	19.39	21.27	18.19
ol	....	1.25	2.43
mg	....	1.39	2.55
il	....	2.00	2.28

NOTES

1. Lapilli (andesite), Goropu Mountains, Papua (anal. F. F. Field).

2. Gray andesite, Radicofani, Tuscany (anal. H. S. Washington, *Amer. Jour. Sci.*, Vol. IX [1900], p. 52).

3. Black andesite, Radicofani, Tuscany (anal. H. S. Washington, *Amer. Jour. Sci.*, Vol. IX [1900], p. 52).

constituent minerals in some, but not all, of the lapilli.

The rock conforms with A. Johannsen's[5] description of a biopyribole ande-

[5] *A Descriptive Petrography of the Igneous Rocks* (Chicago: University of Chicago Press, 1937), Vol. III.

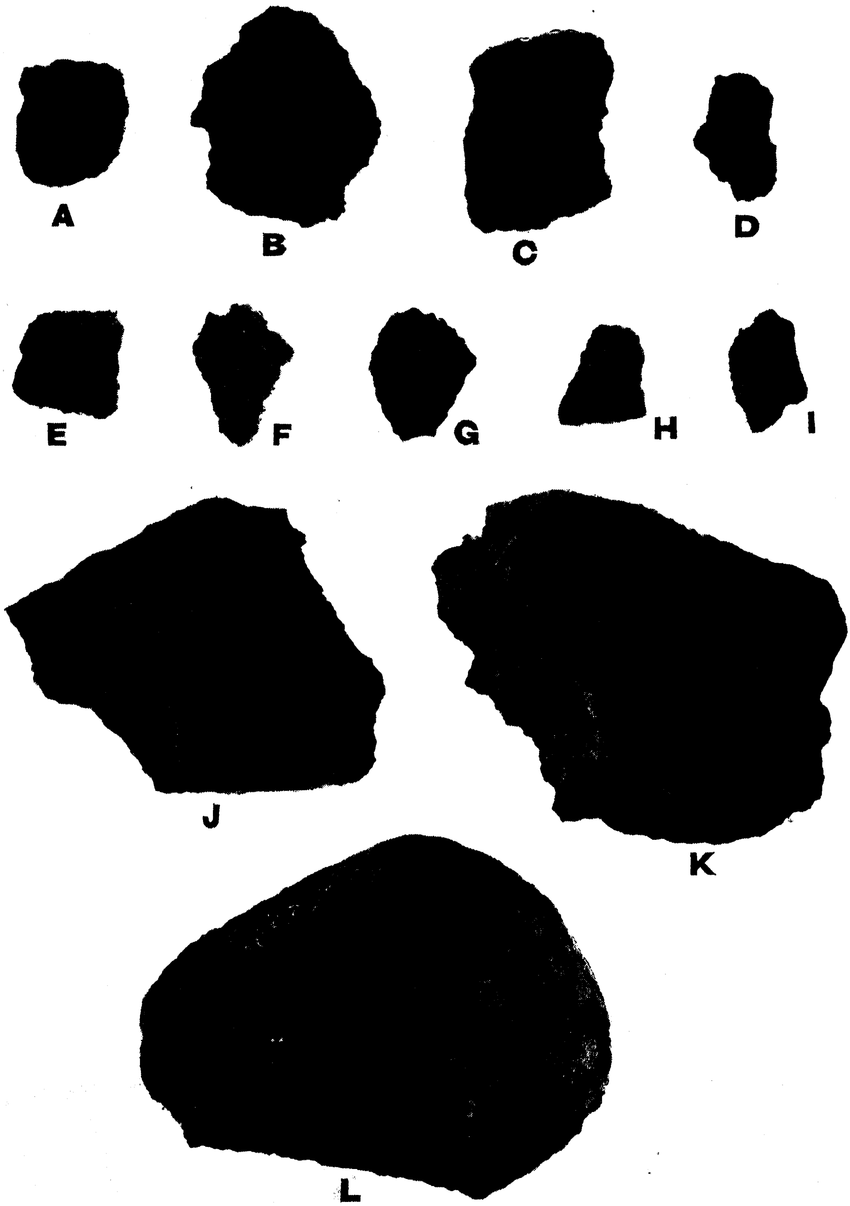

FIG. 3.—Ejectamenta from the Goropu volcano, Papua.

A–I: Lapilli (andesitic) collected from Iu-ai-u; thrown 16 miles by the eruption of December 27, 1943. ×0.7.

J–L: Ejected pebbles from near the vents; eruption of December 27, 1943. Approximately natural size.

site in containing four different ferromagnesian types of minerals, namely, crystals of augite, biotite, hornblende (in two examples), and olivine (Fig. 4), set in a microcrystalline to hyaline base. The chief mineral appears as numerous, small, colorless prisms of augite in subparallel alignment. A few phenocrysts of pale-green augite show partial inversion to hornblende or to biotite; one phenocryst, altered to biotite on the outside, measured $6 \times 2 \times 1\frac{1}{2}$ mm. Biotite (R.I. = 1.613), as brown, elongated plates showing good alignment in the fluidal structures, constitutes the next most abundant crystallized component of the rock. Occasional basal plates of this mineral reveal small inclusions, some of which are remnants of augite, after which the biotite crystallized; others are crystals of apatite. Hornblende is next in abundance in two of the lapilli, forming some of the larger phenocrysts (up to 3 mm. long) in the rock; it is of greenish-brown color, sometimes zoned, sometimes twinned. Olivine is represented by infrequent clots, which show partial resorption and transition to biotite.

The microcrystalline to hyaline base contains abundant minute grains of ilmenite and small laths of andesine. Numerous needles of apatite and minute rounded grains of colorless garnet form accessory minerals in the groundmass. The glassy matrix is grayish to colorless and varies in amount in different lapilli. The garnet is common in one of the lapilli, but scarce in others.

With bromoform of specific gravity 2.88, a heavy-mineral index figure of 15.5 was obtained. Most of the minute garnets were carried up in the bromoform by virtue of being included in the glass of the groundmass; a few, however, were observed as inclusions in augite.

The chemical composition and the norms of the lapilli are indicated in Table 1, column 1, and are compared with two analyses of andesites from Radicofani in Tuscany, Italy. Unusual features of the rock, as disclosed by the chemical analysis, are the low total iron content, the apparent absence of Fe_2O_3, the excess of K_2O over Na_2O, and the high content of MgO, which is slightly in excess of CaO.

Most andesites have lime in excess of magnesia and soda in excess of potash, while iron is generally more abundant. The low iron content of the Goropu lapilli indicates that the olivine and the augite are magnesia-rich varieties. The high content of MgO is a reflection of the presence of olivine crystals and also, taken in conjunction with the absence of Fe_2O_3, suggests that the biotite is a magnesia-rich variety. The high content of MgO in the presence of a relatively high SiO_2 content is anomalous. This may be due to the inclusion in a moderately acid magma of xenocrysts of magnesia-rich minerals, derived from the ultrabasic basement rock through which the volcano has broken in the Goropu Mountains. Alternatively, the lapilli may represent differentiation products within a cupola,[6] from which some of the magnesia-rich xenocrysts may have sunk prior to crystallization. The fact that potash is present in excess of soda and that soda would be used up in the formation of andesine indicates that the residual glass in the lapilli is potash-rich. Some of the potash may have entered into the composition of the biotite, but it appears that, if the rock had become holocrystalline, it would have had as much orthoclase as plagioclase and would then enter into the category of the trachy-

[6] "Tertiary Lavas from the Kerguelen Archipelago," *Repts. British-Australian-New Zealand Antarctic Research Expedition, 1929–1931*, Ser. A., Vol. II, Part 5 (1938), pp. 72–100.

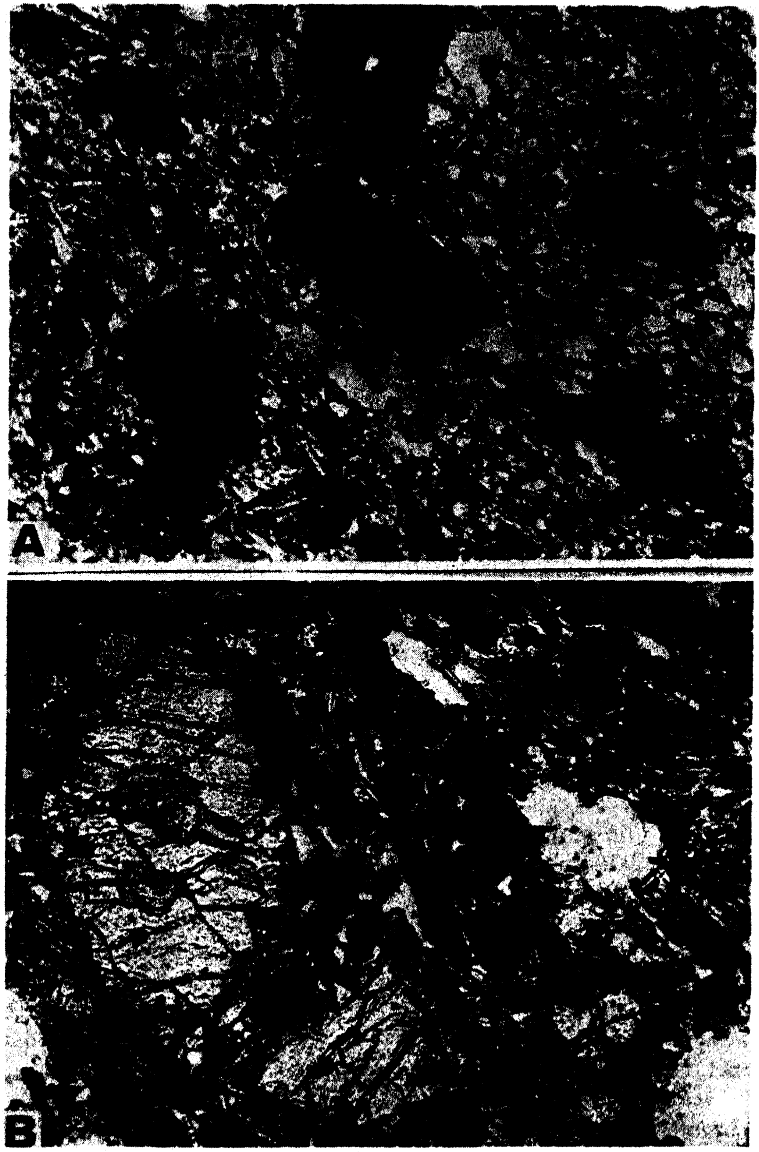

FIG. 4.—Photomicrographs of lapilli (andesitic) from the Goropu volcano, Papua.

A: Hornblende and biotite phenocrysts, and short prisms of augite in a glassy, vesicular groundmass. ×85.

B: Olivine clot and associated biotite in a glassy groundmass containing augite prisms, small feldspar laths, and occasional vesicles. ×100.

andesite group of rocks. The mineralogical and chemical evidence thus indicates that the lapilli from the craters in the Goropu Mountains of Papua represent augite-biotite-hornblende-olivine trachyandesite.

The analyses of two andesites from Radicofani in Tuscany, Italy, provide the nearest analogues to the andesitic lapilli from the Goropu volcano; all three come into the same category—II. 5. 3. 3.—in the Cross, Iddings, Pirsson, Washington classification of rocks.

The three ejected pebbles (Fig. 3, *J–L*) were $2\frac{3}{4} \times 2 \times 1\frac{3}{4}$ inches, $2\frac{1}{2} \times 1\frac{3}{4} \times 1\frac{3}{4}$ inches, and $2 \times 1\frac{1}{2} \times \frac{3}{4}$ inches in size. They were collected from the site of one of the active vents and are "dry pebbles," having been rounded to varying degrees by having been repeatedly thrown up in the throat of the volcano, prior to expulsion from the crater. Each specimen was coated with a thin covering of fine volcanic mud.

Two of the ejected pebbles are of ultrabasic igneous character, and the third intermediate; they represent portions of the wall rock of the vent, up which the volcanic ejectamenta rose. The two ultrabasic ejected pebbles are dark green in color and consist of propylitized serpentine rock with augite. They were probably originally pyroxenite and now contain secondary chlorite, quartz, feldspar (adularia?), limonite, and numerous patches of brownish-gray carbonate, probably magnesite. Some epidote is present in both ejected pebbles, and a vein of zoisite cuts through the serpentine in the more propylitized of the two. These pebbles of ultrabasic rock evidently originated from "the long but broken serpentine belt" associated with the Owen Stanley series and "occurring on the northern slopes of the Main Range from the headwaters of the Waria river to the Peninsula between Milne Bay and the south coast."[7]

The third pebble is a lighter-green, dense, fine-textured rock with a microporphyritic character. Microphenocrysts of augite are set in a microcrystalline to cryptocrystalline and hyaline groundmass. Andesine is recognizable among the groundmass minerals, and its minute, lathlike crystals are arranged sometimes in a subparallel fluidal fashion, sometimes in a felted mass, so that the ground mass is thus partially trachytic to pilotaxitic in structure. From the evidence of thin-section examination, the rock is best described as an augite andesite. It was carried up from depth as a solid rock and ejected as such.

These three ejected pebbles supply some evidence of the nature of the basement rock through which the new volcanic vents have broken on the northern flanks of the Goropu Mountains in Papua.

A sample of the dust which fell on Port Moresby on August 31, 1944, was composed principally of rock and mineral fragments which averaged 0.2 mm. in size. The particles consist of andesitic glass with embedded prisms of augite, individual plates of fresh and chloritized biotite, occasional fragments of hornblende, augite, and olivine. Rare fragments of quartz, calcite, oligoclase feldspar, and one crystal of rutile, observed in two mounted preparations of the dust, were probably picked up from the atmosphere during the movement of the dust cloud from the Goropu volcano to Port Moresby. Shreds of vegetable matter were also present in the dust.

REMARKS

The geological position of the volcanic vents is a matter of considerable interest,

[7] Stanley, p. 29 of ftn. 1 (1923).

as no volcanic phenomena had previously been reported in the scientific literature from this particular locality. No detailed geological map of the Goropu volcanic area exists, and the basis for boundaries drawn through this zone on the general geological map of Papua (of which Fig. 1 of this paper is a portion) has not been stated. E. R. Stanley[8] reported that recent outflows of lavas and pyroclastics had occurred about the headwaters of the Musa and Kumusi rivers, 65 miles west-northwest of the recently active volcanic zone, stating:

> Trachyte lavas were met with near Vi Creek on the Mimai river, and about 2 miles up the Awaru river from its junction with the Moni. At this latter locality, I discovered a series of hot springs on the left bank of the river about two chains from the levée. The atmosphere for a considerable distance round was contaminated with sulphuretted hydrogen. The ground near the vents is very hot, cracked and devoid of vegetation. The vents are from 18 inches to two feet in diameter, incrusted with siliceous sinter, geyserite, sulphur, and small red incrustations consisting of selenium and cinnabar. The vents are in schistose country, about which there are large masses of volcanic agglomerate. The natives evidently did not know of this occurrence and were very frightened when approaching it, especially when the small eruptions occurred every four and a half minutes.

Stanley (1923) also stated that thermal areas are seen to advantage on the islands of Normanby and Fergusson and about Mount Victory, which was then regarded as the only active volcano in the Territory of Papua.

A zone of volcanic and fumarolic activity (sulphur and steam emanations), possibly connected with rifts, extends from the D'Entrecasteaux Islands, through the Cape Vogel and Cape Nelson peninsulas (see Fig. 1) to the headwaters of the Kumusi River. R. W. Van Bemmelen,[9] in his recent analysis of the geotectonic structure of New Guinea according to his "Undation Theory," refers to this volcanic zone on the north coast of southeastern New Guinea as follows:

> This zone of young volcanic activity extends eastwards in the D'Entrecasteaux Group with Mt. Dawila on Goodenough Island. One gets the impression that here, since the Lower Miocene orogenesis .... a small secondary undation cycle spreads from the Central Range towards the north. This so-called "D'Entrecasteaux-system" has a volcanic inner arc (D'Entrecasteaux Islands with the volcanic zone along the northern side of the tail of New Guinea) and a non-volcanic outer arc (Trobriand Islands and Woodlark Island).

Figure 5 shows the position of these arcs in relation to the volcanic zones of the Territory of New Guinea, which have been studied recently by N. H. Fisher[10] and L. C. Noakes,[11] and to other structural elements recognized in the New Guinea area.

The numerals and letters in the Structural Sketch Map of New Guinea (Fig. 2) signify:

1. Neogenic–Quaternary volcanic zones or volcanic inner arcs
2. Folded and overthrust nonvolcanic arc of the Banda System

2*a*. Median depression of the Banda outer arc

3. Nonvolcanic outer arcs of the Bismarck and the D'Entrecasteaux systems
4. Central Range of New Guinea
5. Northern Divide Range
6. Merauke ridge (*sensu lato*)

[8] Ftn. 2 (1919).

[9] "The Geotectonic Structure of New Guinea," *De Ingenieur in Nederlandsch-Indie*, Yaarg. 6, No. 2, Vol. IV (1939), pp. 17–28.

[10] "Geology and Vulcanology of Blanche Bay and the Surrounding Area, New Britain," *Geol. Bull. No. 1, Territory of New Guinea* (1939); "Report on the Volcanoes of the Territory of New Guinea," *Geol. Bull. No. 2, Territory of New Guinea* (1939); "The Volcanoes of the Mandated Territory of New Guinea," *Proc. 6th Pacific Sci. Cong.*, Vol. II (1940), pp. 889–94.

[11] "Geological Reports on New Britain," *Geol. Bull. No. 3, Territory of New Guinea* (1942).

7. Australian continental block
8. Melanesian semicontinental region
8a. Crystalline schists of Melanesian border

(The northern and southern depression zones of the Island of New Guinea are left blank. The volcanic and nonvolcanic arcs of the D'Entrecasteaux System are marked, respectively, *V* and *N*).

The andesitic character of the Goropu volcano, as evidenced by the lapilli, fits in well with the fact that the geologically Recent and present-day volcanoes girdling the Pacific Ocean erupt andesites. Many of these are hypersthene-bearing varieties,[12] but this mineral does not occur in the new Goropu volcanic ejectamenta which have been investigated. Fisher[13] described most of the recent New Guinea and New Britain volcanoes as basaltic in character, but in parts andesites have been recorded from thin-section examinations. Comparison of the chemical analyses of several Japanese and other andesitic volcanoes in the circum-Pacific belt with that of the Goropu volcano shows that the New Guinea example has distinctive characters (see Table 1); these have already been elaborated; no analyses of other New Guinea or of any New Britain andesites of geologically Recent age are available for comparison.

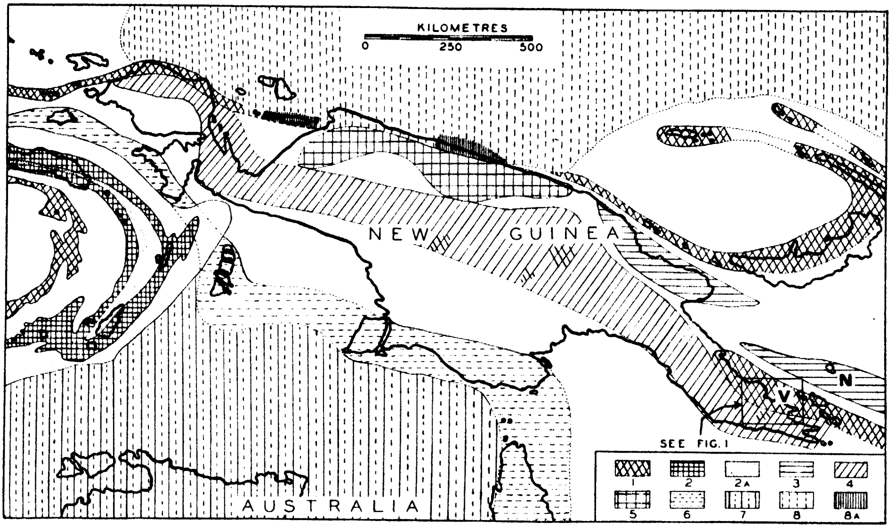

FIG. 5.—Structural sketch map of New Guinea. (After R. W. Van Bemmelen, 1939)

Computation of the standard mineral composition of average andesites shows a certain excess of free silica. This is expressed in the Goropu volcanic lapilli by the presence of 3 per cent normative quartz, and the free silica here must lie occult in the glassy to microcrystalline groundmass. In addition to excess silica, however, there occur sporadic olivine crystals; rocks with such associations are regarded by A. Lacroix[14] as doliomorphic.

Apparently the lapilli and, most likely,

[12] G. W. Tyrrell, *The Principles of Petrology* (London: Methuen & Co., Ltd., 1934).

[13] Ftn. 10 (1939).

[14] "La notion de type doliomorphe en lithologie," *Comp. rend. Acad. sci., Paris*, Vol. CLXXVII (1923), pp. 661–65.

the large blocks of vesicular rock reported by patrols as occurring along Uiaku Creek represent parts of an almost solidified plug or cupola which blocked the initial rift developed above the magma chamber, or they represent an even deeper-seated plastic magma and may have formed part of a chilled margin at the roof of the magma chamber. The plug or chilled margin ultimately became disrupted by gas pressure when the accumulated gases below exerted sufficient force for explosive activity to take place. Up to the present time this activity has not been followed by the pouring-out of lavas.

Some measure of differentiation and crystal resorption had occurred prior to eruption, as evidenced by the alteration of olivine and augite phenocrysts to biotite. Although N. L. Bowen[15] regarded volatile components as of minor importance in the fractional crystallization of magmas, he nevertheless accepted C. N. Fenner's[16] hypothesis of a process of gas transfer as causing igneous differentiation, as far as it affected magma bodies open to the air, where a streaming of gas bubbles through the magma could bring about a differential transfer of materials. Bowen[17] considered that, at best, surface lavas and volcanic conduits were unimportant seats of igneous differentiation. It seems, however, that such effects may be locally important, and, although transient, the process of gas streaming through the magma below the Goropu volcanic vents has apparently had marked effects. Besides resulting in vesiculation, the passage of escaping gases and aqueous substances through a magma from which olivine and augite crystals had already separated has apparently played a decisive role in the formation of hornblende. Owing to a transient enrichment in volatile components, equilibrium changes caused suitable conditions from which wet-fusion minerals could form, and so hornblende crystallized. Equilibrium under these conditions, however, was not maintained, because small augite prisms were developed in the groundmass when volatiles had escaped from the magma, that is, the magma had returned to a state from which dry-fusion minerals again crystallized. The extrusion of the partially solidified magma in the form of lapilli at this stage interrupted the normal plutonic processes involving the resorption and sinking of olivine and augite crystals and resulted in the retention of an assemblage of abnormal mineralogical types; the olivine persisted only by virtue of the rapidity of cooling consequent upon the rapidity of extrusion.

Rapid ascent of the plastic material through the vents, under the stimulus of great expansive forces created by the further accumulation of gases below the more plastic magma, resulted in marked decreases in the temperature and pressure of the partially solidified rock. Consequent quick chilling of the interstitial liquid led to the formation of a glassy matrix charged with numerous small vesicles. This may have occurred partly during ascent through the conduit, but probably mainly during flight through the atmosphere, when discharged as ejectamenta. During these final stages of consolidation, a flow structure was developed in the lapilli, to a greater degree in some than in others.

It would appear that the magma reservoir or, at the least, the upper parts of it are probably in a well-advanced stage of solidification in the Goropu region of volcanic activity. No recent flows

[15] *The Evolution of the Igneous Rocks* (Princeton: Princeton University Press, 1928).

[16] "The Katmai Magmatic Province," *Jour. Geol.* Vol. XXXIV (1926), pp. 675–772.

[17] P. 294 of ftn. 15 (1928).

of lava are known from the immediate vicinity of this center of vulcanism, and, moreover, the lapilli indicate that considerable crystallization had gone on in depth prior to the explosive eruptions. As far as the Papuan region as a whole is concerned, vulcanism in general is apparently approaching the dying stages, because the last flows of andesitic lavas known to have been extruded are recorded as having occurred in Pliocene to Pleistocene times at Mount Dayman and in the Cape Nelson region.[18] Known activity in historical times has been mainly explosive or else has produced only sinter and gaseous and sulphurous emanations—phenomena usually interpreted as indicating the dying stages of volcanic activity.

From the available eyewitness accounts and according to B. G. Escher's[19] classification of central eruptions, it seems that the Goropu volcano probably belongs to a less violent class of the *Perret* type of eruptions, that is, one of the destructive variety connected with very strong gas pressure, a very deep magma chamber, and a viscous lava. A high gas pressure is indicated in an eruption by a high cauliflower cloud of ash and steam, and, according to Escher,[20] high gas pressure is observable only when the amount of escaping gas is very great, as evidenced by the long duration of a violent eruption or by the coring and scouring effect on the vent. The columns of crater-clouds from the Goropu volcano were of considerable magnitude after the explosive eruptions. The continued emission of gas, steam, and ash through the vents between December, 1943, and July, 1944, with three strong eruptions during that period, and the tearing-away, carrying-up, and ejection of portions of the walls of the vents indicate the development of high gas pressure in the Goropu region of vulcanicity. Such a condition is probably to be compared with the intermediate gas phase, as described by Perret[21] for the 1906 Vesuvius eruption.

The Goropu vents have not, as far as is known, emitted any lavas, and it therefore appears that the effusive liquid phase is absent. On the other hand, the vents cannot be classified as entirely explosive in type, because for a goodly proportion of their period of activity to date there have been steadily issuing currents of gas from most of the vents. Such gaseous emissions are not to be looked upon as coming completely into the category of "explosions." Only occasionally have explosions occurred; this may explain why the cones have so far remained as relatively insignificant features of the Goropu volcano; gas, steam, and fine ash are the principal constituents emitted, and the fine ash is carried away for some considerable distance from the centers of eruption.

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[18] Stanley, ftn. 1 (1923).

[19] "On a Classification of Central Eruptions According to Gas Pressure of the Magma and Viscosity of the Lava," *Leidsche geologische Mededeel.*, Vol. VI (1933), pp. 45–49.

[20] *Ibid.*, p. 46.

[21] Pp. 44–47 of ftn. 3 (1924).

GEOMORPHIC TERMINOLOGY AND CLASSIFICATION OF LAND MASSES

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ABSTRACT

The words "plains," "plateaus," and "mountains" have been used by W. M. Davis, Douglas Johnson, and A. K. Lobeck to mean crustal masses made up of flat-lying strata or deformed and intruded rocks. The writer criticizes this usage and proposes that it be abandoned in favor of the commonly understood topographic meanings of the words. An alternative set of terms, already often used, is suggested for the various land-mass types. It employs only common geologic words, which describe the underlying structures. A geomorphic classification of areas of intrusive, metamorphic, and complexly deformed rocks is proposed.

INTRODUCTION

In the teaching of geomorphic principles, map interpretation, and regional geomorphology it is necessary to classify land masses on the basis of their geologic structure, in keeping with W. M. Davis'[1] principle that all land forms are the product of three basic elements: *structure*, *process*, and *stage*. Land forms underlain by a given type of geologic structure may be divided into two major groups. The first consists of land forms produced directly by epeirogenic, orogenic, or volcanic activity. These have been termed "initial" or "constructional" land forms and are dominant in initial and youthful stages of the erosion cycle. The second group consists of land forms developed by gradational agents, which carve the relatively large initial land forms into a variety of smaller "sequential" or "destructional" forms.

While these broad concepts of land-form development have proved invaluable, the writer has encountered difficulty in explaining to students of elementary geomorphology certain of the terms applied by Davis,[2] Douglas Johnson,[3] and A. K. Lobeck[4] to specific classes of geologic structures, grouped under the headings "Plains and Plateaus" and "Mountains." In tabular form is given the system employed for many years by Johnson and Lobeck, and fully published by the latter.[5]

1. Plains and plateaus (simple structure)
   a) Interior plains
   b) Plateaus
   c) Coastal plains
2. Mountains (disturbed structures)
   a) Folded mountains
   b) Dome mountains
   c) Block mountains
   d) Complex mountains
3. Volcanoes and related forms

Criticism of this terminology rests upon the following points: (1) The words

[1] "The Geographical Cycle," *Geog. Jour.*, Vol. XIV (1899), pp. 481–504.

[2] *Geographical Essays*, ed. Douglas Johnson (Boston: Ginn & Co., 1909).

[3] References to Johnson's terminology and classification of land forms are based upon his class lecture notes.

[4] *Panoroma of Physiographic Types* (New York: Geographical Press, Columbia University, 1926); *Geomorphology* (New York: McGraw-Hill Book Co., 1939).

[5] See ftn. 4 (1939).

"plain" and "plateau" have been taken from their usual meaning in terms of topography and have been redefined as crustal masses whose geologic structure consists of horizontal strata; (2) the word "mountains" likewise has been deprived of its usual meaning as a topographic feature and has been redefined as any large crustal mass of deformed rock; (3) the class "complex mountains" includes a wide variety of rocks and structures, certain of which have simple, rather than complex, topographic expression.

Discussions with graduate students and experimental modification of this terminology in teaching have indicated that the difficulties can easily be alleviated without changing Davis' principles of land-form development. Moreover, an advantage in using geological and geographical terms in their generally accepted sense, instead of as redefined and highly specialized terms, is to be gained through the easier understanding of geomorphic literature by those in other fields who cannot take time to refresh their memories regarding special meanings. Seemingly unsatisfactory elements of the terminology are here examined, and alternatives are proposed.

The writer is indebted to several persons who have kindly read and criticized the manuscript. These include Professors A. K. Lobeck and W. H. Bucher, of Columbia University; Professor Kirk Bryan, of Harvard University; Professor Karl Ver Steeg, of the College of Wooster; Professor Henry S. Sharp, of Barnard College; and Mr. Charles W. Carlston, of the United States Geological Survey. It should not be inferred, however, that these persons necessarily indorse the opinions stated here.

PLAINS AND PLATEAUS

REVIEW OF USAGE

The practice of calling regions of horizontal strata "plains" and "plateaus" seems to have been introduced by Davis in 1884.[6] But in 1893[7] he referred to the New England Upland as a plateau and to the "plateau of the middle Rhine." Here he clearly used the conventional geographical meaning of the word "plateau." By his reference to regions of complex geologic structure, he ruled out any implication of horizontal structure. In 1894 Davis[8] referred to "plains and plateaus of horizontal structure" as if feeling the need of accompanying the words with a translation into terms of geologic structure. In 1896 Davis'[9] use of the title "Plains of Marine and Subaerial Denudation," as well as the repeated use of "plain" throughout the paper as a surface of low relief, shows that on occasion he did abandon entirely the meaning of the word as "horizontal structure." Soon after the turn of the century, the use of "plains" and "plateaus" for land masses of horizontal structure had become well established in Davis' writings.[10]

Douglas Johnson subscribed to Davis' terminology and classification of the constructional land forms. In map-inter-

[6] "Geographic Classification, Illustrated by a Study of Plains, Plateaus, and Their Derivatives" (abstract), *Proc. Amer. Acad. Arts and Sci.*, Vol. XXXIII (1884), pp. 428–32.

[7] W. M. Davis, "The Improvement of Geographical Teaching," *Nat. Geog. Mag.*, Vol. V (1893), pp. 68–75.

[8] "Physical Geography as a University Study," *Jour. Geol.*, Vol. II (1894), p. 96

[9] "Plains of Marine and Subaerial Denudation," *Bull. Geol. Soc. Amer.*, Vol. VII (1896), pp. 377–98.

[10] *Physical Geography* (Boston: Ginn & Co.,1898); *Die erklärende Beschreibung der Landformen* (Leipzig, 1912).

pretation classes he used the combination term "plains-plateaus" to designate any region underlain by horizontal strata. Lobeck has followed Davis and Johnson in the *Panorama of Physiographic Types*[11] and the textbook *Geomorphology*.[12]

Fenneman has followed Davis in the use of "plain" and "plateau" and has exerted a dominant influence in naming and describing the geomorphic provinces of the United States.[13]

A. D. Howard and L. E. Spock[14] have recently used "plain" and "plateau" in the sense of horizontal strata, although they present a new system of land-form classification.

A survey of the literature reveals that many geomorphologists and the larger proportion of geologists in other fields and geographers have preferred to use the words "plain" and "plateau" much as they are defined by *Webster's New International Dictionary*.[15] This source defines "plain" as "level land" or a "broad stretch of land having few inequalities of surface." "Plateau" is defined as "a tract of land of considerable summit area, which is high, or distinctly above adjacent land on at least one side; a tableland." In neither definition is mention made of underlying rock structure. A few random examples of this usage are given below.

In his essay on the development of physiographic features, J. W. Powell[16] used "plains" and "plateaus" for relatively flat land surfaces. James Geikie,[17] treating the origin and development of land forms, used "plains" and "plateaus" in the same way. C. A. Cotton[18] has consistently used these words in their topographic sense. For example, he states that past periods of peneplanation in mountains "may be recognizable as such owing to the preservation of plateaux or plateau remnants." When referring to regions of low relief underlain by horizontal strata, he keeps the distinction between surface form and structure clear by such terms as "stripped structural plateau" or "structural plateau."[19]

E. de Martonne[20] employs a system of land-form classification based upon structure and including classes similar to those used by Davis, Johnson, and Lobeck; but he uses the word "plain" to describe land surfaces of low relief and does not apply it to strongly elevated or maturely dissected horizontal strata. The restriction of "plain" and "plateau" to land surfaces, irrespective of rock structure, is evident in his statement that there are regions of plains and plateaus where geologic studies have revealed bedrock of highly complex tectonic structures.

C. R. Longwell, A. Knopf, and R. F. Flint[21] do not follow Davis' terminology. They state:

[11] See ftn. 4 (1926).

[12] See ftn. 4 (1939).

[13] "Physiographic Divisions of the United States," *Annals Assoc. Amer. Geog.*, Vol. XVIII (1928), pp. 261–353; *Physiography of the Western United States* (New York: McGraw-Hill Book Co., 1931). *Physiography of the Eastern United States* (New York: McGraw-Hill Book Co., 1938).

[14] "Classification of Landforms," *Jour. Geomorph.*, Vol. III (1940), pp. 332–45.

[15] 2d ed., Springfield, Mass.: G. & C. Merriam Co., 1942.

[16] "Physiographic Features," *Nat. Geog. Soc., Mono. I* (1895), pp. 34–40.

[17] *Earth Sculpture* (New York: G. P. Putnam's Sons, 1898), pp. 335–39.

[18] *Landscape* (Cambridge: Cambridge University Press, 1941), p. 83.

[19] *Ibid.*, pp. 101–2.

[20] *Traité de géographie physique*, Vol. II (Paris: Librairie Armand Colin, 1926), pp. 563–68, 756–76, 807.

[21] *Outlines of Physical Geology* (New York: John Wiley & Sons, 1941), p. 296.

> High plateaus formed by any process are attacked by stream erosion, and during a late stage in the destruction some residuals in the more favored locations have sufficient height, in relation to their surroundings, to be called mountains.

As an example they cite the Catskill Mountains. They also add:

> In some plateaus the rocks are steeply tilted strata whose edges were cut down to a nearly uniform level at a low elevation by previous erosion.

Here, clearly, the term "plateau" is applied to a topographic feature, quite apart from any particular rock structure underneath.

In recent works on geography examined by the writer, the words "plain" and "plateau" are used in the topographic sense. For example, Preston James[22] defines "plain" as an area of low relief, generally less than 500 feet. He states that a plateau stands distinctly above neighboring areas, at least on one side, and has a considerable part of its surface at or near summit level. V. C. Finch and G. T. Trewartha[23] discuss at length the development of landscape features through the activity of erosional processes upon geologic structures, but they classify land forms primarily on the basis of relief and only secondarily on the basis of rock structure or geologic process. "Plain" and "plateau" refer to surface form of the land, regardless of the nature of the underlying rocks and structures. George B. Cressey[24] restricts "plain" and "plateau" to areas which are essentially flat or gently rolling with slopes up to 5°. These forms constitute major groups in a classification based solely on surface configuration.

[22] *An Outline of Geography* (Boston: Ginn & Co., 1935), p. 66.

[23] *Elements of Geography* (New York: McGraw-Hill Book Co., 1936), pp. 317–427.

[24] *Asia's Lands and Peoples* (New York: McGraw-Hill Book Co., 1944), pp. 16–17.

OBJECTIONS TO DAVIS' USE OF "PLAINS" AND "PLATEAUS"

Specific criticisms which may be urged against Davis' use of "plains" and "plateaus" are as follows:

1. This use conflicts with current geographical, geological, and popular usage and has not taken hold except among a limited group of Davis', Johnson's, and Lobeck's students. While it is frequently desirable to restrict for scientific use the meanings of words popularly employed in a broad sense, it seems quite unjustifiable to use the words with an entirely different meaning. Moreover, there is need for the words "plain" and "plateau" in the description of topographic forms, just as there is need for the words "slope," "hilltop," "peak," "ridge," "spur," or "col."

2. The words "plain" and "plateau" carry within themselves no suggestion of geologic structure, although it was for this very purpose that they were used by Davis and his students. It is necessary to translate these terms into geologic language whenever they are used among persons other than geomorphologists. It would seem more reasonable to use, instead, the term "horizontal strata"[25] (or "flat-lying strata") for this structural class. The words "plain" and "plateau" may then be returned to the category of descriptive words used in connection with stage of development.

DISCUSSION OF THE CLASS "HORIZONTAL STRATA"

In urging the use of "horizontal strata" (or "flat-lying strata"), the writer is aware that strata are rarely, if

[25] Pp. 44–72 of ftn. 17. This chapter provides a good example of the use of this term.

ever, precisely horizontal; but it is customary even to refer to the surfaces of water bodies as horizontal, although they are deformed by tidal forces, winds, or gravitational attraction of adjacent land masses. It is intended that strata be classed as horizontal as long as they give rise to a dominantly dendritic drainage pattern composed of insequent streams. In addition to sedimentary strata, extensive areas and thicknesses of flat-lying lavas are included, the expressions "horizontal lavas" or "horizontal flows" comprising convenient specific designation.

In classification and terminology, difficulty is likely to arise in regard to the structures intermediate between horizontal strata and distinctly folded, domed, or block-faulted strata. Extremely low dips give cuestas and subsequent lowlands with roughly trellis or rectangular drainage systems developed on a large scale, even though the greater proportion of the area is covered with a dendritic valley system. Often the larger pattern is detected only on small-scale maps and is not apparent when individual topographic quadrangles on the scale of 1:125,000 or larger are examined. Where inclination of strata has perceptible influence upon even the smaller elements of topography, the land mass may be termed "faintly inclined strata" or "gently folded strata," replacing such terms as "tilted or scarped plains," and "folded plains-plateaus." If the terms used are descriptive, no rigid system need be adhered to.

COASTAL PLAINS

From the foregoing discussion it might appear that some basis exists for finding a new term to replace "coastal plain" to designate extensive, recently emerged coastal belts underlain by appreciable thicknesses of seaward-sloping marine strata. Retention of "coastal plain" seems desirable for the following reasons: (1) The term is widely understood and is used in all branches of geology and geography. Introduction of a new term would serve no useful purpose while the old one is in good standing. (2) The term "coastal plain" is descriptive and does not violate accepted usage of the included words. Coastal plains have surfaces of low relief, not only in young and old stages, but often in maturity as well. Nevertheless, the term carries no information as to underlying structure and cannot be regarded as a fully satisfactory name for a structural class.

Coastal plains may be considered a class of equal importance with "horizontal strata" or a subclass under the latter. Lobeck treats coastal plains in a separate chapter and includes a discussion of ancient coastal plains of Paleozoic strata, but in his preliminary treatment of classification of land forms he makes no mention of coastal plains, thus implying that they do not comprise a separate class.[26]

MOUNTAINS

REVIEW OF USAGE

Davis[27] summarized as follows his classification of geologic structures for purposes of geomorphic description:

> It will suffice to recognize two great structural groups: first, the groups of horizontal structures, including plains, plateaus, and their derivatives, for which no single name has been suggested; second, the group of disordered structures, including mountains and their derivatives, likewise without a single name. The second group may be more elaborately subdivided than the first.

Although Davis later came to employ "plains and plateaus" and "mountains"

[26] Pp. 6–7, 14–15, 439–68, of ftn. 4 (1939).

[27] P. 482 of ftn. 1.

to designate these two groups, it is significant that he expressed some doubt or dissatisfaction with the nomenclature.

Douglas Johnson went still further than Davis in associating "mountains" with disturbed structures and dissociating the word entirely from its common meaning of bold-relief features. In the classroom he would designate any region of disturbed rocks as "mountains," even though it had been reduced to a peneplain. Johnson recognized four classes of mountains: folded mountains, dome mountains, block mountains, and complex mountains.

R. S. Tarr and L. Martin[28] followed Davis in restricting "mountains" to parts of the earth's crust which have been disturbed by diastrophic movement. They noted that "plateaus may be so dissected as to simulate rugged mountain topography, as in the Catskills, and mountains may be worn down to such low relief as to resemble a plain, as in the Piedmont Plateau." Here the difference between popular usage and Davis' terminology is evident.

Fenneman,[29] while adhering closely to Davis' use of "plain" and "plateau," has not always used "mountains" to signify structure alone. Thus in a tabular summary of physiographic divisions he has employed such expressions as "mountains of disordered crystalline rocks" and "mountains due to erosion of open folds," implying a distinction between the mountainous terrain and the rock structure beneath; but elsewhere in this paper he has simply used the terms "complex mountains," "block mountains," and "domed mountains." Lobeck[30] has followed the terminology developed by Johnson and employs the same four classes of mountains.

Despite the influence of Davis and his students, many geologists and geographers have continued to use "mountain" as it is defined by *Webtser's New International Dictionary*,[31] namely, "any part of a land mass which projects conspicuously above its surroundings: in general, an elevation higher than a hill, with comparatively steep slopes, ... and relatively small summit area." This authority further adds that most mountains are produced by crustal deformation but sometimes result from erosion of plateaus. Some random examples of this usage are noted below.

J. W. Powell[32] used "mountain" to signify a type of topography. From the wide variety of origins which he assigned to mountains it is clear that no structural implication was intended. R. D. Salisbury[33] treated as one of the major mountain groups those produced by the erosion of horizontal strata and cited as examples the Catskill Mountains in New York, the Timpanogas Mountains in Utah, and the Castle Group in Colorado. Other groups include volcanic mountains and mountains due to intrusion and uplift, folding, or faulting.

C. A. Cotton[34] has generally avoided Davis' usage and recognizes a distinction between mountains as relief features and disturbed structures which may underlie them. For example, he has used the heading "drainage of mountainous areas of folded rocks."

[28] *College Physiography* (New York: Macmillan Co., 1914), pp. 525–26.

[29] Pp. 274–79 of ftn. 13 (1928).

[30] Ftn. 4 (1939).

[31] Ftn. 15.

[32] Pp. 40–44 of ftn. 16.

[33] *Physiography* (New York: Henry Holt & Co., 1907), pp. 437–57.

[34] *Geomorphology of New Zealand* (Wellington, N.Z.: New Zealand Board of Science & Art, 1922), p. 85.

Longwell, Knopf, and Flint emphasize the close association of mountainous topography with disordered structures, but their use of "mountains" is clearly in a topographic meaning. As noted in the quotation cited earlier, these authors include regions of maturely dissected horizontal strata under the heading of "mountains." The usage is also clearly revealed by their reference to "a dome high enough to be a mountain."[35]

Among structural geologists, "mountains" seems to be used in the conventional manner. W. H. Bucher[36] rarely uses the term except in proper names. Instead, he employs descriptive terms emphasizing the nature of the deformation. M. P. Billings[37] likewise rarely refers to "mountains." One notable exception is "fault-block mountains," in which "the topography expresses the underlying structure more or less faithfully."

In most geography works examined by the writer, "mountains" refers to rugged topography. For example, Preston James[38] uses "mountain lands" to mean rugged terrain with sufficient relief to produce marked vertical zoning of vegetation. Finch and Trewartha[39] state that mountains are characterized by steep slopes, small summit areas, and strong relief. They distinguish mountains from other land forms on the basis of surface configuration. Cressey[40] uses a similar terminology and classification. Hills and mountains are distinguished from plains and plateaus on the basis of steepness of slopes, not on differences of lithology or structure.

Lobeck[41] has recently published a somewhat revised terminology for regions of disturbed geologic structures. It emphasizes the structures and restricts "mountains" to topographic forms of strong relief. The classes are entitled "dipping structures," "domes and basins," "block mountains," "folded structures," "complex structures," and "volcanoes." Thus for all except "block mountains" the word "mountains" has been dropped. His use of "plains" and "plateaus" for regions of horizontal strata remains unchanged.

OBJECTIONS TO DAVIS' USE OF "MOUNTAINS"

Specific criticisms of the use of "mountains" to signify land masses of disordered structure regardless of stage of erosion are as follows:

1. It conflicts with the generally accepted popular meaning of the word which has been used with little or no further qualification by the large majority of geographers and geologists. Confusion arises when the student of elementary geomorphology is told that the Piedmont Plateau is classified as "complex mountains"; that the broad Triassic lowlands of northern New Jersey are "block mountains" (or "folded mountains"); and that, on the other hand, towering peaks of the Uintas are in the group "plains and plateaus." A still more striking example might be the broad Hudson Valley lowland above Newburgh, classified as "folded mountains" by Davis, Johnson, and Lobeck. Adjacent to it are the rugged Catskill

[35] Pp. 295–318 of ftn. 21.

[36] *The Deformation of the Earth's Crust* (Princeton: Princeton University Press, 1933).

[37] *Structural Geology* (New York: Prentice-Hall, 1942), p. 195.

[38] Pp. 307–8 of ftn. 22.

[39] Pp. 443–71 of ftn. 23.

[40] Pp. 16–17 of ftn. 24.

[41] A. K. Lobeck and W. J. Tellington, *Military Maps and Air Photographs* (New York: McGraw-Hill Book Co., 1944), pp. 104–44.

Mountains, which they would classify, instead, as "plains and plateaus."

No good purpose is served by attempting to enforce a strange meaning of the word "mountains" upon persons who have always used it in a way acceptable to the best authorities. Because the old usage will not be abandoned by the vast majority, it would seem left to the followers of Davis and Johnson to choose between conformity or the perpetuation of a ceaseless struggle which only detracts from the true worth of Davis' basic principles of land-form evolution.

2. Application of the term "mountains" to all areas of appreciably folded, domed, or faulted strata imparts undeserved grandeur to structures of small size or limited deformation. For example, some areas of domed strata exhibit typical radial and annular drainage patterns, cuestas, and hogbacks, yet would scarcely qualify either as strongly deformed structures or as mountainous terrain. The Weald uplift in southeast England is treated by Lobeck in a chapter entitled "Dome Mountains," along with more apparent mountainous domes, such as the Black Hills.[42] Even the very broad gentle domes and basins of the interior eastern United States are included in this chapter, though they could scarcely be regarded as deformed structures.

PROPOSED MODIFICATION OF THE TERMINOLOGY OF DISTURBED STRUCTURES

A simple and effective modification of the terminology of disturbed structures as given by Davis, Johnson, and Lobeck may be had by omitting the word "mountains" wherever it appears. Thus "folded mountains" becomes "folds" or "folded strata"; "dome mountains" becomes "domes" or "domed strata"; "block mountains" becomes "fault blocks"; and "complex mountains" becomes "complex structures" or "complexly deformed rocks." The last class is discussed later and is stated to be in need of subdivision.

Advantages of these changes would be felt in two ways: (1) Words relating to topographic form are excluded and are reserved for discussions of topography produced in various stages of development in the cycle of erosion, while all words retained refer to rock structure; and (2) provision is made for inclusion of structures not sufficiently deformed or elevated to produce mountainous topography in any stage of their development.

Of the four classes of disturbed rocks, fault blocks and complex structures may be discussed further. The term "block mountains" has received unusually wide use, even by those who do not follow Johnson and Lobeck's system of terminology and classification, because mountain ranges normally result whenever tilted crustal blocks or horsts are greatly elevated. Nevertheless, the inadvisability of including the word "mountains" in the term has been expressed by other writers. Cotton prefers to restrict "block mountains" to actual mountain ranges carved from large uplifted earth blocks bounded on one or both sides by fault scarps.[43]

Marland Billings uses the terms "tilted fault block" and "horst" for structures which Davis, Johnson, or Lobeck would have classified as "block mountains."[44] Both Cotton and Billings recognize the need for a purely geological term which will include grabens, downtilted parts of fault blocks, and blocks only slightly faulted or tilted. In the

[42] Pp. 503–42 of ftn. 4 (1939).

[43] P. 151 of ftn. 34; *Geomorphology* (London: Whitcombe & Tombs, Ltd., 1942), pp. 154–61.

[44] P. 195 of ftn. 37.

judgment of the present writer, "block mountains" can be used as a convenient designation for actual mountain ranges produced by faulting but should not be applied to the structural class as a whole or to up-faulted blocks which have since been reduced to pediment or peneplain surfaces.

A possible additional structural class is suggested by the occurrence of sizable areas in which sedimentary strata are moderately to steeply inclined in one direction only. Most of these examples prove to be merely parts of much larger structural units whose form is not readily apparent within a limited area. For example, the dissected East Kaibab monocline in southern Utah appears as a broad belt of parallel ridges and valleys, in which all the strata dip eastward or northeastward. Although the monocline as a whole would perhaps be referred to the class "folds," a limited area might be classified "homoclinal strata." The same term could be applied to the belts of hogbacks and cuestas along the east base of the Colorado Front Range and to foothill belts of various ranges of the Rockies. While these may, in reality, be only limbs of great anticlinal folds, the exposure of broad belts of crystalline rocks along the center of the arches effectively separates the sedimentary limbs and makes desirable the designation "homoclinal strata" for each belt. Good examples of this are the small ranges flanking the Sweetwater arch in central Wyoming. Another example of homoclinal strata is in the Triassic Lowland of northern New Jersey. While the Triassic basin as a whole might be classed as "tilted fault blocks," areas the size of a 15-minute quadrangle may show fairly uniform westward dips, with no evidence of faulting and no means of ascertaining whether the gross structure is a large tilted fault block or a large fold. In view of these considerations there seems to be a good case for use of the term "homoclinal strata"; but, because such areas are usually, if not always, parts of larger structures, the term would logically refer to subclasses under "folds," "domes," and "fault blocks."

The class "complex mountains," as employed by Johnson and Lobeck, includes a great variety of structures and resultant land forms, some of which differ among themselves, both in structure and in topography, to an even greater extent than do certain of the other major classes of disturbed structures. Johnson made a classroom practice of including in "complex mountains" all intrusive and metamorphic rocks, as well as any combinations of other structures which do not show distinctive and simple relief forms. The wide variety in types has been fully recognized by Lobeck, who subdivides the class "complex mountains" into (1) igneous areas, (2) metamorphic areas, and (3) strongly disturbed sedimentary areas.[45] The present writer would, however, suggest a somewhat different grouping, as follows:

1. *Homogeneous crystallines.*—Included here are land masses composed of massive intrusive rocks or "plutons,"[46] and metamorphic rocks, principally schists and gneisses, whose composition is essentially homogeneous throughout and results in dendritic drainage development. Furthermore, because such a mass is anything but complex in its behavior to denudational processes, it should not be retained in the class of complex structures but should be given the rank of a major structural class.

Areas of homogeneous crystalline rocks are widespread. Examples may be

[45] Pp. 624–25 of ftn. 4 (1939).

[46] P. 261 of ftn. 37.

found in the southern Idaho[47] and the Piedmont.[48] Two unusually striking examples of uniform dendritic drainage pattern and slopes may be cited. In the area of the Mount Gleason, California, Quadrangle map (1:24,000), this topography is developed on anorthosites, diorites, and granodiorites of the San Gabriel Mountains block.[49] On the Dome Rock Mountains, Arizona, Quadrangle map (1:62,500) is shown a fine-textured dendritic topography developed on Archean (?) schists, gneisses, or granites.[50] A few of the larger valleys are rectilinear and trend northwest-southeast, suggesting fault zones, but the areas referred to lie between these zones. Where homogeneous masses are faulted or strongly jointed, as in the Elizabethtown, New York, Quadrangle or Yosemite National Park, the terms "faulted homogeneous crystallines" or "strongly jointed homogeneous crystallines" may be employed.

2. *Belted metamorphics*—Included in this group are areas of metamorphosed sedimentary and igneous rocks, folded and faulted in such a manner as to give distinct, but irregular, elongate, subparallel ridges and valleys resulting from the etching-out of weaker limestones or schists from between bands of quartzites, gneisses, or younger linear intrusions. Examples may be found in the New Jersey and Hudson Highlands (Schunemunk and Ramapo, New York, quadrangles) and in parts of the Blue Ridge and Piedmont provinces (Antietam, Maryland, Virginia, West Virginia, and Westminister, Maryland, quadrangles).

3. *Complexly deformed or intruded rocks.*—In this group would be placed all masses of highly complex structure and lithology which give rise to great irregularity of topographic expression. Here one or more periods of folding, faulting, and intrusion may have occurred. The topography may show hills or mountain masses varying locally in height, shape, and trend and in steepness of slopes. Drainage patterns may be irregular and not resolvable into any one of the systematic patterns characteristic of the other constructional land forms. Under such circumstances, map interpretation of structure and lithology is extremely difficult, if not impossible. Good examples may be found in New England (Averill, Vermont, New Hampshire, Quadrangle and Winnepesauke, New Hampshire, Quadrangle), in the northern Rockies (Silvertip, Montana, Quadrangle), in the Black Hills (Deadwood and Harney Peak, South Dakota, quadrangles), and in central Arizona (Bradshaw Mountains Quadrangle).

The three types described above are not always clearly distinguishable, and intermediate types are numerous; but the fact that gradations may occur in nature does not justify lumping together distinctive types under the older term "complex mountains." Gradations likewise occur between regions of horizontal strata and those of folds, domes, and fault blocks, but this fact has not prevented the use of separate structural classes. The significant point brought

[47] Maps of the Sawtooth and Yellow Pine Quadrangles (U.S. Geol. Surv.) illustrate topography typical of the Idaho batholith. The Sawtooth map, 1:125,000, is old and generalized. The Yellow Pine map, 1:62,500, is recent and detailed. Glaciation, which produced numerous cirques and troughs, has destroyed much of the uniformity of slopes and drainage pattern.

[48] The Columbia, S.C., Quadrangle, 1:125,000 (U.S. Geol. Surv.) map shows topography produced on granite, which underlies much of the Piedmont from Virginia to Georgia.

[49] William J. Miller, "Geology of the Western San Gabriel Mountains of California," *Univ. Calif. Pub. Math. Phys. Sci.*, Vol. I (1934), pp. 1–114.

[50] N. H. Darton *et. al.*, "Geologic Map of Arizona," *Ariz. Bur. Mines and U.S. Geol. Surv.* (1924).

forward here is the need for recognition of homogeneous bodies of igneous and metamorphic rock as comprising a relatively simple kind of land mass to be distinguished from those of genuinely complex structure and topography.

TABULATION AND CONCLUSIONS

In Table 1 is shown a comparison between the terminology originated by Davis and developed further by Johnson and Lobeck, and the modified terminology proposed by the writer.

TABLE 1

COMPARISON OF TERMINOLOGIES USED IN CLASSIFICATION OF LAND MASSES

Classification Based on Initial Land Forms (Davis, Johnson, and Lobeck)	Classification Based on Geologic Structure (Strahler)
1. Plains-plateaus	1. Undisturbed structures
a) Interior plains }	a) Horizontal strata (or flat-lying strata)
b) Plateaus }	
c) Coastal plains	b) Coastal plains
2. Mountains	2. Disturbed structures
a) Folded mountains	a) Folds
b) Dome mountains	b) Domes
c) Block mountains	c) Fault blocks
d) Complex mountains	d) Homogeneous crystallines
1) Igneous areas	e) Belted metamorphics
2) Metamorphic areas	f) Complexly deformed or intruded rocks
3) Strongly disturbed sedimentary areas	
3. Volcanoes and related forms	3. Volcanoes and related forms

Whereas the older terminology referred to the initial land forms produced by diastrophism and vulcanism and could not properly be applied either to the sequential land forms or to the underlying rock structures, the newer terminology clearly classifies regions according to their geologic structure. The "constructional" or "initial" land forms should be treated as features of a stage in the erosion cycle and not identified with geologic structures. Confusion seems to have followed from the attempt to make the term "land form," which refers to surface configuration, synonymous with "structure," which refers to subsurface conditions.

The proposed revision of terminology employs no newly coined words and does not alter the genetic classification of initial and sequential land forms built up by Davis, Johnson, and Lobeck. With the exception of "coastal plain," all terms refer to geologic structure or lithology rather than to topography, thereby rendering the terminology consistent with Davis' first element of the geomorphic triad—structure, process, and stage—and reserving topographic terms for the third element.

The revision results in removal of words which have not been generally accepted with the special definitions imposed upon them and which have tended to cause confusion among students of elementary geomorphology, as well as among workers in other fields of geology and in geography. Although the abandonment of Davis' usage of certain terms is proposed, it is hoped that the understanding and application of his explanatory system of land-form description will instead be facilitated.

CORRELATION BETWEEN FISH DISTRIBUTION AND PLEISTOCENE HYDROGRAPHY IN EASTERN CALIFORNIA AND SOUTHWESTERN NEVADA, WITH A MAP OF THE PLEISTOCENE WATERS[1]

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ABSTRACT

During late Pleistocene time an integrated river system occupied several of the desert basins in eastern California and southwestern Nevada, with Death Valley as the sump. A study of the Recent and fossil fishes of the region supports the physiographic evidence for the existence of this drainage and presents zoögeographic data which strongly suggest connections between this system and the Lahontan basin to the north, as well as with the Colorado River basin to the south and east. Both the physiographic and the fish evidence harmonize. Detailed maps of the Pleistocene and Recent hydrography of the southern Great Basin are presented, and two new lakes are mapped and named.

INTRODUCTION

For more than half a century geologists have studied and described Pleistocene lakes and drainage systems from the arid region of the western United States. Information regarding the best known of these former bodies of water, Lake Bonneville[2] and Lake Lahontan,[3] is based on extensive physiographic data, and their history is known in comparatively great detail. Knowledge concerning the considerable number of lesser lakes,[4] which were more or less contemporaneous with Bonneville and Lahontan, is much more fragmentary and calls for renewed investigation.

At some time during the Pleistocene epoch nearly all the enclosed basins in the West probably held lakes of varying size and duration. Only a very few of these basins have received the careful study which they deserve, and, in general, only the more recent history is at all clear. One can seldom do more than speculate on the conditions which may have prevailed in middle or early Pleistocene times.

DEATH VALLEY SYSTEM

There is unmistakable physiographic evidence that during the latter part of Pleistocene time an integrated river system existed in eastern California and adjoining parts of Nevada (Fig. 1). I have named this drainage the "Death Valley system"[5] because the Death Valley trough formed the sump for its waters. From this terminus the tributaries spread out in all directions to drain an area nearly one-fifth that of the state of California (Fig. 2, insert). The detailed history of this river system appears to have been very complicated, and much of the story remains to be deciphered.

The late physiographic history of the

[1] Excerpt from a dissertation submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in the University of Michigan. Published by permission of the Secretary of the Smithsonian Institution.

[2] Grove Karl Gilbert, "Lake Bonneville," *U.S. Geol. Surv. Mono. 1* (1890). Pp. i–xx+1–438; Figs. 1–51; Pls. 1–51; 1 map.

[3] Israel Cook Russell, "Geological History of Lake Lahontan, a Quaternary Lake of Northwestern Nevada," *U.S. Geol. Surv. Mono. 11* (1885). Pp. i–xiv+1–288; Figs. 1–35*a–c*; Pls. 1–46.

[4] Oscar E. Meinzer, "Map of the Pleistocene Lakes of the Basin-and-Range Province and Its Significance," *Bull. Geol Soc. Amer.*, Vol. XXXIII (1922), pp. 541–52, Figs. 1–4.

[5] Robert R. Miller, "*Cyprinodon salinus*, a New Species of Fish from Death Valley, California," *Copeia*, No. 2 (1943), p. 69.

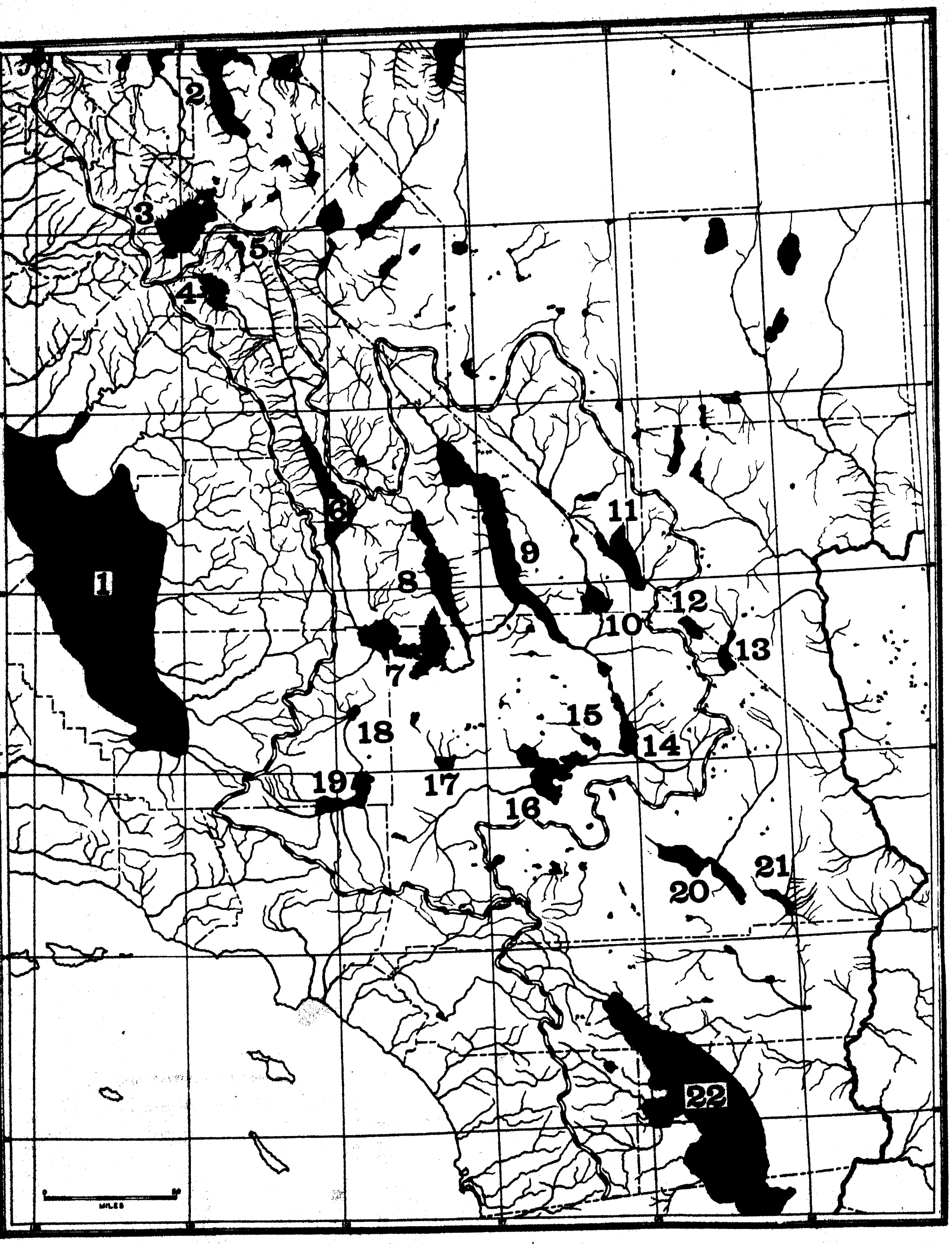

FIG. 1.—Maximum extent of the Pleistocene waters of the southern Great Basin and adjacent areas. The wider boundary line marks the separation between coastal and interior or Colorado River drainages. The narrower line indicates the outline of the Death Valley system (see insert, Fig. 2). Modified after U.S. Geological Survey maps of California and Nevada.

rivers and lakes in this area is divisible into at least two stages, which E. Blackwelder[6] has tentatively correlated with the Tahoe and Tioga stages of glaciation in the near-by Sierra Nevadas. These stages, in turn, are believed to have been approximately contemporaneous with the earliest and latest stages of the Wisconsin or last continental glaciation of eastern North America.[7] Still earlier phases also seem to be represented.

It has been established by H. S. Gale[8] and Blackwelder[9] that Owens River was formerly tributary to Death Valley

[6] Eliot Blackwelder, "Pleistocene Glaciation in the Sierra Nevada and Basin Ranges," *Bull. Geol. Soc. Amer.*, Vol. XLII (1931), p. 918.

[7] "Lake Manly: An Extinct Lake of Death Valley," *Geog. Rev.*, Vol. XXIII (1933), pp. 464–71, Figs. 1–4; "Pleistocene Lake Tecopa," *Pan-Amer. Geol.*, Vol. LXIII (1936), p. 311.

[8] "Salines in the Owens, Searles, and Panamint Basins, Southeastern California," *U.S. Geol. Surv. Bull. 580-L* (1914), pp. i–vi and 251–323, Figs. 58–88, Pls. 5–7.

[9] Ftn. 6 (1933).

KEY TO FIGURE 1

Pleistocene Lake	Authorities
1. Lake Tulare	Blake (1857) (*Pacific Railroad Expl. and Surv.*, Vol. V (1856); last map at end of geological report)
2. Walker Lake arm of Lake Lahontan	Russell (1885)
3. Lake Mono	Russell (1889)*
4. Lake Long Valley	Mayo (1934)* (*Science*, Vol. LXXX [new ser.], pp. 95–96); Jenkins (1938) (Geologic Map of California; *Calif. Dept. Nat. Res., Div. Mines*); original observations
5. Lake Adobe†	Original observations (1938, 1942)
6. Lake Owens	Gale (1914)*; Jenkins (1938)
7. Lake Searles	Gale (1914)*
8. Lake Panamint	Gale (1914)*
9. Lake Manly	Blackwelder (1933)*
10. Lake Tecopa	Noble (1931) (*U.S. Geol. Surv. Bull. 820*, pp. 64–68, Pl. 11*A*); Thompson (1929), Pl. 8; Blackwelder (1936)*; Jenkins (1938); original observations
11. Lake Pahrump	Waring (1920); original observations (see text)
12. Lake Mesquite	Jenkins (1938)
13. Lake Ivanpah	Waring (1920); Jenkins (1938)
14. Lake Mohave	Thompson (1921)* (*Jour. Wash. Acad. Sci.*, Vol. XI, pp. 423–24), (1929); Bode (1935) (*Southwest Mus. Papers*, Vol. XI, pp. 108–18)
15. Little Lake Mohave	Thompson (1921,* 1929); Jenkins (1938); original observations
16. Lake Manix	Buwalda (1914)* (*Bull. Univ. Calif. Dept. Geol.*, Vol. VII, pp. 443–64); Blackwelder and Ellsworth (1936); Jenkins (1938); original observations
17. Lake Harper	Jenkins (1938)
18. Lake Kane	Thompson (1929), Pl. 8
19. Lake Thompson‡	Thompson (1929); Jenkins (1938)
20. Lake Amboy	Thompson (1929)*; Jenkins (1938)
21. Lake Ward	Thompson (1929)*; Jenkins (1938)
22. Lake Cahuilla	Blake (1907)* (*Nat. Geog. Mag.*, Vol. XVIII, p. 830); U.S. Geol. Surv., Salton Sink quadrangle; Mexican portion after Sykes (1937) (*Carnegie Inst. Wash., Pub. 460*, Pl. 1), modified by Rogers (1939) (*San Diego Mus. Papers*, Vol. III, Map 1)

* The asterisks denote the authors who proposed definite names for ancient lakes.

† Name proposed from the name of the valley occupied by the Pleistocene lake.

‡ It is proposed that this Pleistocene lake be named in honor of the late David Grosh Thompson, who carried out extensive studies on the ancient lakes of the Mohave Desert region.

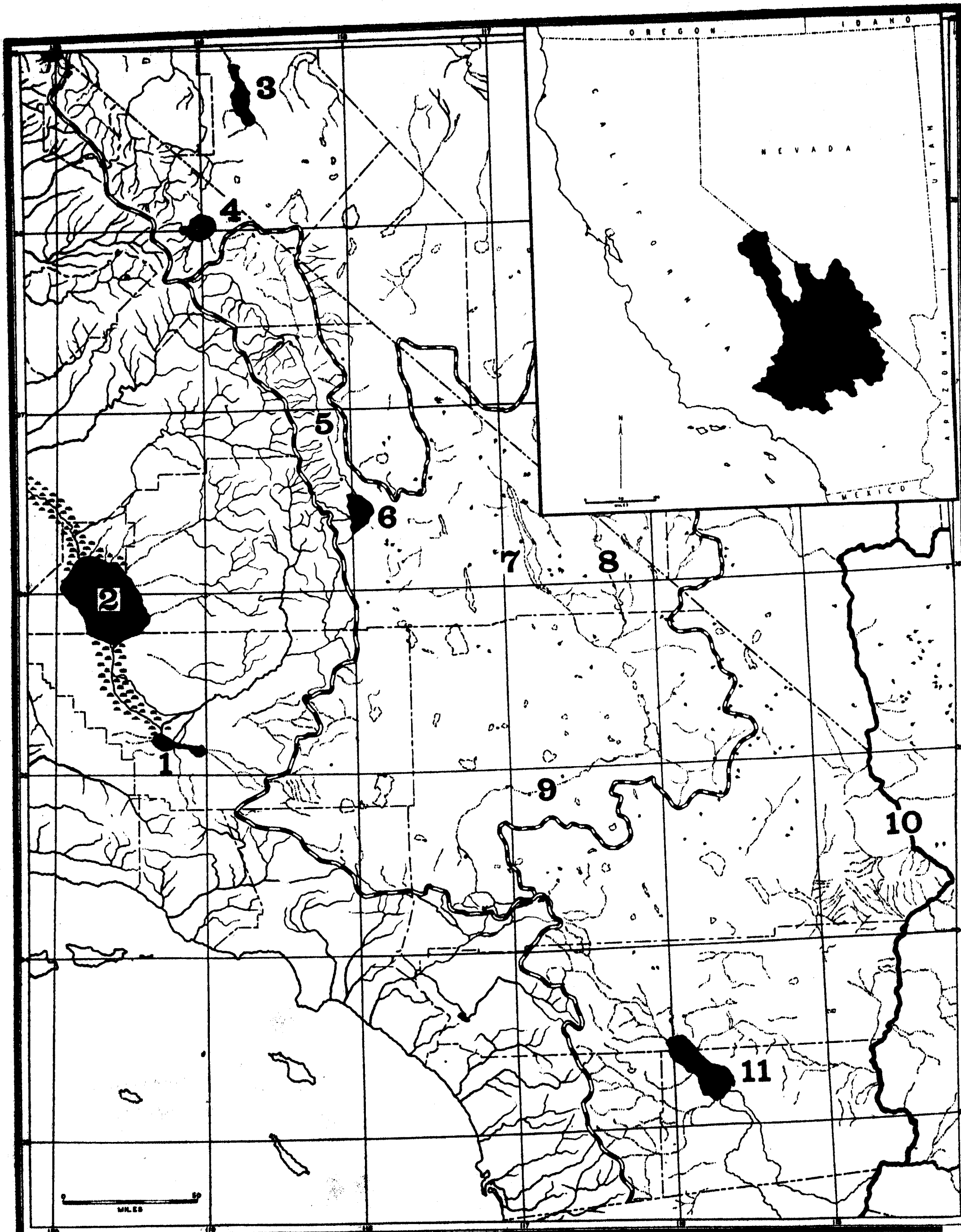

FIG. 2.—Recent hydrography of the southern Great Basin and adjacent areas. The wider boundary line m the separation between coastal and interior or Colorado River drainages. The narrower line indicates the outline o Death Valley system (see insert). For comparison with the Pleistocene waters see Figure 1. In the area blocked by the insert there are no Recent lakes.

through a chain of lakes beginning with the basin of Owens Lake and ending in Death Valley (Fig. 1). Owens River filled Lake Owens[10] to overflowing and continued southward and eastward to the basins of Lake China and Lake Searles. At maximum extent,[11] Lake Searles covered both of these basins and was about 640 feet deep. At a later stage[12] both Lake China and Lake Searles were separate bodies connected by a channel through Salt Wells Valley. During the higher stage, Lake Searles overflowed at the southeastern end to fill Panamint Valley and form Lake Panamint, a narrow body of water 60 miles long and over 900 feet deep. It is believed that at its greatest height Lake Panamint discharged into Lake Manly, the terminal lake of the series in Death Valley (Fig. 1, No. 9). This body of water was about 100 miles long and 600 feet deep.[13] At the same time that waters poured into Lake Manly from Owens Valley, Death Valley probably received the discharge of both the Amargosa and Mohave rivers, whose conjoined waters entered from the south.

[10] In this account the name of the Pleistocene lake follows the word "Lake," whereas the name used for the Recent body of water precedes the word "Lake."

[11] Gale, Pl. 7 in ftn. 8.

[12] Eliot Blackwelder, "Lakes of Two Ages in Searles Basin, California," *Bull. Geol. Soc. Amer.*, Vol. LII (1941), pp. 1943–44.

[13] L. F. Noble, "Note on a Colemanite Deposit near Shoshone, Calif., with a Sketch of the Geology of a Part of Amargosa Valley," *U.S. Geol. Surv. Bull. 785* (1926), pp. 63–75, Fig. 14; Blackwelder, ftn. 6 (1933).

During this period, tentatively correlated by Blackwelder with the Tahoe glacial stage, a continuous waterway probably connected Owens Valley with the Amargosa and Mohave river basins. It was therefore possible for fish life to move between those now isolated drainages.

In addition to the present catchment area of the Amargosa River basin, there are both physiographic data and fish evidence (discussed below) to support the view that Pahrump Valley, along the California-Nevada boundary (Fig. 1, No. 11), filled and discharged into the Amargosa River. Similarly, a Pleistocene lake filled Adobe Valley (Fig. 1, No. 5), and its waters rose to cut an impressive outlet into the now virtually dry North Fork of Owens River.

CORRELATION BETWEEN FISH DISTRIBUTION AND HYDROGRAPHY

A systematic study of the Recent and fossil fish fauna of the Death Valley system[14] presents evidence which has a definite bearing on physiographic conclusions regarding the Pleistocene hydrography of this region. These data not only demonstrate the former continuity of the drainage but strongly favor the view

[14] Robert R. Miller, "The Fishes of the Relict Waters of the Pleistocene Death Valley Stream System" (typewritten Doctorate dissertation, University of Michigan, 1944), pp. i–v + 1–326, Figs. 1–33, Pls. 1–22, Maps 1–6; "Four New Species of Fossil Cyprinodont Fishes from Eastern California," *Jour. Wash. Acad. Sci.*, Vol. XXXV (1945), pp. 315–21, Figs. 1–4.

KEY TO FIGURE 2

1. Kern and Buena Vista Lakes
2. Tulare Lake
3. Walker Lake
4. Mono Lake
5. Owens River
6. Owens Lake
7. Death Valley
8. Amargosa River
9. Mohave River
10. Colorado River
11. Salton Sea

Kern, Buena Vista, and Tulare lakes are mapped as they existed in 1876. These lakes are now dry basins.

that the Death Valley system, or a preceding drainage of even greater extent, had connections with the Lahontan basin to the north as well as with the Colorado basin to the east. Let us examine the evidence.

Cyprinodon, a genus of small fishes of the family Cyprinodontidae found in temperate and tropical fresh, brackish, and salt waters, is present in the system in Owens Valley, Death Valley, and the middle and lower Amargosa River basin. Its absence from the Mohave River is attributed to the lack of a suitable habitat. It is elsewhere known in the West only from the lower Colorado River basin,[15] and the species of that drainage obviously was derived from relatives to the east where the genus reaches its maximum development. The conclusions drawn are that (1) the occurrence of *Cyprinodon* in the Death Valley system demands that a connection once existed between that drainage and the Colorado River basin and (2) the now isolated basins of Owens Valley, Death Valley, and the Amargosa River were once united by waterways. The discovery of a fossil *Cyprinodon* in Death Valley, in beds of late Tertiary or early Quaternary age, indicates that the connection with the Colorado was an ancient one.

The presence of the minnow *Siphateles* in the Death Valley system is also highly significant in an interpretation of past hydrography. *Siphateles* is unknown from the Colorado River basin, either as a Recent or as a fossil member, but is abundantly represented in the Lahontan basin and other systems to the north and west.[16] In the Death Valley system it inhabits only Mohave and Owens rivers, and fossils referred to this genus have been found in Pleistocene lake beds of those two drainages.[17] Again we can conclude that (1) the Death Valley system was connected at one time with the Lahontan basin of western Nevada and (2) the now widely separated Owens and Mohave rivers were united by a waterway at some time during the Pleistocene epoch.

Empetrichthys, another cyprinodont fish, is confined to the Death Valley system, where it is known only from Pahrump Valley, an isolated basin, and Ash Meadows, of the Amargosa River drainage. Both of these localities lie in extreme southern Nye County, Nevada, and are separated by a rather low, alluvial divide.[18] E. E. Free[19] indicated that Pahrump Valley was tributary to the Amargosa River during the existence of Lake Lahontan. As far as I am aware, no evidence has been presented to prove or disprove his contention, but he made several erroneous claims for connections of other desert basins in that period.[20]

[15] Robert R. Miller, "The Status of *Cyprinodon macularius* and *Cyprinodon nevadensis*, Two Desert Fishes of Western North America," *Univ. Mich., Mus. Zoöl., Occasional Papers, No. 473* (1943), pp. 1–25, Fig. 1, Pls. 1–7.

[16] John Otterbein Snyder, "The Relationships of the Fish Fauna of the Lakes of Southeastern Oregon," *Bull. U.S. Bur. Fish.* [1907], Vol. XXVII (1908), pp. 78, 86–97, Figs. 3–4; "The Fishes of the Lahontan System of Nevada and Northeastern California," *Bull. U.S. Bur. Fish.* [1915]; Vol. XXXV (1917), pp. 60–67.

[17] Eliot Blackwelder and Elmer W. Ellsworth, "Pleistocene Lakes of the Afton Basin, California," *Amer. Jour. Sci.*, Vol. XXXI (1936), pp. 453–63, Figs. 1–4; Miller, pp. 91–93 of ftn. 14 (1944).

[18] Gerald A. Waring, "Ground Water in Pahrump Mesquite, and Ivanpah Valleys, Nevada and California," *U.S. Geol. Surv. Water-Supply Paper 450* (1920), Pl. 8.

[19] "The Topographical Features of the Desert Basins of the United States with Reference to the Possible Occurrence of Potash," *U.S. Dept. Agric. Bull. 54* (1914), pp. 43–44.

[20] Carl L. Hubbs and Robert R. Miller, "The Fish Faunas of the Desert Basins of the Western

That a waterway connected Pahrump Valley and the Amargosa basin during Pleistocene time seems very likely from both physiographic and zoögeographic evidence. The elevation of the lake-bed remnants of Lake Pahrump,[21] near the Pahrump Ranch, is about 50 feet higher than that of the lowest divide between Pahrump Valley and the Amargosa basin.[22] The elevated position of the beds is attributable to the known tilting and faulting which have taken place since their deposition. The presence of *Empetrichthys* in the two basins supports the physiographic conclusion that they were once part of a common drainage.

One other fish—a sucker of the genus *Catostomus*—presents further, though less convincing, evidence in favor of the view that the Lahontan and Death Valley systems were once united. This fish, confined to the Owens River basin, very probably was derived from *Catostomus tahoensis*, its nearest relative, which occurs in the Lahontan basin. Although the genus is represented in the lower Colorado River by *C. latipinnis*, the relationships of the Recent species argue against a belief that the Owens River sucker was derived from an ancestral Colorado River form rather than from one in the Lahontan basin. The late Dr. J. O. Snyder believed that all the fishes inhabiting Owens Valley, except *Cyprinodon*, were identical with species in the Lahontan basin.[23]

Presumably the ancestral sucker and minnow (*Siphateles*) moved southward from the Lahontan basin into Owens Valley by way of the Mono basin during or before the existence of Pleistocene Lake Mono (Fig. 1, No. 3), at a time prior to the formation of the Mono Craters. Although I. C. Russell[24] found no evidence that the Mono and Lahontan basins were connected during the existence of Lake Mono, it is quite likely, as he hinted, that a waterway was established between these basins during an earlier stage by way of what are now the East Fork of the Walker River and Aurora Valley.[25] After fish life entered the Mono basin, a hydrographic connection probably was established with the headwater region of Owens River in Long Valley, and the species spread southward. Dr. W. C. Putnam, of the University of California at Los Angeles, who has investigated the region, wrote[26] that he believes there is good physiographic evidence for such a connection. At a later date the Mono Craters were formed, blocking this drainage and perhaps destroying the fish fauna of the Mono basin by a deluge of volcanic ash. Such a hypothesis could explain why this basin is now devoid of native fishes and is similar to the hypothesis advanced by D. S. Jordan[27] to explain the destruction of fish and other life on the Yellowstone plateau.

Preliminary study of one other minnow of the genus *Rhinichthys* in the

United States, Correlated with Recent and Pleistocene Hydrography," in: "The Great Basin, with Emphasis on Glacial and Postglacial Times" (unpublished manuscript).

[21] It is proposed that "Lake Pahrump" (roughly mapped herein as Fig. 1, No. 11) be the name of the Pleistocene body of water which formerly filled a large part of Pahrump Valley.

[22] Ftn. 18.

[23] "An Account of Some Fishes from Owens River, California," *Proc. U.S. Nat. Mus.*, Vol. LIV (1917), pp. 201–5.

[24] "Quaternary History of Mono Valley, California," *U.S. Geol. Surv. 8th Ann. Rept.* (1886–87), Part I (1889), pp. 300–301.

[25] Aurora Valley contained a shallow Pleistocene lake shown on Fig. 1 near the upper end of Lake Mono (No. 3).

[26] Personal communication.

[27] "A Reconnoissance of the Streams and Lakes of the Yellowstone National Park, Wyoming, in the Interest of the United States Fish Commission," *Bull. U.S. Fish Com.* [1889], Vol. IX (1891), p. 43.

Death Valley system tends to support another hypothetical waterway which, by stream capture, may have transferred fish of this genus from a tributary of the Colorado into the Amargosa River, now a flood tributary of Death Valley. *Rhinichthys* is found in the Death Valley system only in Owens Valley and the Amargosa River. Its absence from the headwaters of the Mohave River is an enigma, which may be solved when more details of the Pleistocene hydrography are known. Although the evidence is not conclusive, because the problem has not been fully studied, it is very likely that the ancestral Amargosa River stock did not come from Owens River (which almost surely received its stock from the Lahontan basin) but from the Colorado River basin. A *Rhinichthys* is known from Las Vegas Creek, a flood tributary of the Colorado, and the form inhabiting the Amargosa River may have been derived from an ancestral type which was once more widespread in the Las Vegas region. James Gilluly[28] described physiographic evidence for a connection across the alluvial divide separating the Las Vegas and the Amargosa basins. An area of some 150 square miles between Charleston and Point of Rocks in Nevada (see U.S. Geol. Surv., Las Vegas and Furnace Creek quadrangles) was formerly tributary to Indian Springs Valley but has been captured by a tributary of Amargosa River. Indian Springs Valley, a northwestern extension of the Las Vegas trough, formerly held a lake[29] which presumably had no outlet at the stage described by Carpenter but which may have had an earlier (mid-Pleistocene?) discharge south and east to the Colorado River or its antecedent.[30] That *Cyprinodon* also entered the Death Valley system by this route is most unlikely, as this genus is not adapted for life in the current and never seeks the higher tributaries.

WATERWAY BETWEEN DEATH VALLEY AND THE COLORADO RIVER BASIN

A hydrographic connection between Death Valley and the Colorado River already has been suggested by geologists.[31] A series of troughs extending southward and eastward from Death Valley may represent the route along which such a connection once existed. In geographic sequence these troughs are: the Soda-Silver Lake basin, which was occupied by Pleistocene Lake Mohave (Fig. 1, No. 14); the Ludlow basin just to the south; the Bristol-Cadiz basin, the site of Pleistocene Lake Amboy (Fig. 1, No. 20); then either an adjacent, unnamed basin to the south or Danby basin, Pleistocene Lake Ward (Fig. 1, No. 21), to the east. If a drainage ever followed this line of troughs, the physiographic evidence has been erased by subsequent erosion, regrading, and vulcanism. Blackwelder and Ellsworth[32] hypothesized that an immense Pleistocene lake filled Death Valley and the trough to the south, finally overflowing into the Bristol-Cadiz-Danby trough east of Ludlow, and that from there the waters continued to the Colorado River. There is no concrete evidence that such a lake or outlet channel ever existed; but, when it is realized that the

[28] "Possible Desert-Basin Integration in Utah," *Jour. Geol.*, Vol. XXXVII (1929), p. 682.

[29] Everett Carpenter, "Ground Water in Southeastern Nevada," *U.S. Geol. Surv. Water-Supply Paper 365* (1915), p. 72, Pl. 1. On Fig. 1, this lake is the largest one northward of No. 11.

[30] Hubbs and Miller, ftn. 20.

[31] Blackwelder, ftn. 6 (1933); Eliot Blackwelder, "Origin of the Colorado River," *Bull. Geol. Soc. Amer.*, Vol. XLV (1934), p. 562; Blackwelder and Ellsworth, ftn. 17.

[32] Ftn. 17.

Grand Canyon probably has been cut since mid-Pleistocene time, it is not difficult to understand how the evidence for such a connection might have been completely erased.

There is also the possibility that the Mohave River had a temporary connection with the Colorado while maintaining a normal discharge toward Death Valley. Such a drainage relationship, on a very small scale, is effected at the present time when, at its mouth near Baxter, the Mohave alternately discharges northward into Cronese basin (remnant of Pleistocene Little Lake Mohave) and then eastward into Soda Lake basin (Pleistocene Lake Mohave). Before Lake Manix (Fig. 1, No. 16) was drained, Mohave River stood at a much higher level in the outlet channel (which is now Afton Canyon) and could have discharged, temporarily at least, alternately eastward (into the basin of Lake Mohave) and south-southeastward toward Ludlow. The divide between the basin of Soda Lake and Ludlow is alluvial and low, and the divide between Ludlow and Amboy, of rather recent lava,[33] may have been low enough at that time to have been topped by the flooding waters.

It may even be suggested that the Mohave River formerly followed a course south of its present one along a line connecting Barstow and Ludlow and continuing eastward to the Colorado River. The divide west of Ludlow is only 75 feet higher than at Ash Hill, east of Ludlow. Thompson,[34] in describing the valley in which Ludlow is situated, wrote: "It is possible that the great Barstow-Bristol trough, whether it is an erosion valley or a fault trough, is older than the Tertiary Lavas." The vulcanism which occurred during Pleistocene time may have altered the course of Mohave River, forcing it to fill the large basin east of Barstow to form Lake Manix. Since the lowest rim of this lake lay at the northeast, Mohave River cut for itself a new course, which it has followed since.

Moreover, N. H. Darton and others[35] wrote of the Bristol-Cadiz trough: "The origin of this basin has not been fully ascertained, but as the depression is completely surrounded by a rock rim it cannot be due entirely to erosion and probably has resulted from tilting of a portion of an old stream valley." Also Thompson,[36] in writing of this trough, said: "Between Ash Hill and Klondike, north of the railway, two wide washes from 20 to 40 feet deep come from the hills on the north. These washes are so much larger than the washes elsewhere on the alluvial slopes in the valley that a question arises as to their origin." Ash Hill is the volcanic divide separating the Ludlow and Bristol-Cadiz basins. According to free,[37] who postulated late Pleistocene connections with abandon, the Bristol-Cadiz and Danby basins drained to the Colorado River during Lahontan time.

In a recent paper[38] the minnow *Gila orcuttii* was regarded as native to the Mohave River. If this should be true, it would have an important bearing on a hydrographic connection between Pleistocene Mohave River and the Colorado

[33] David G. Thompson, "The Mohave Desert Region, California," *U.S. Geol. Surv. Water-Supply Paper 578* (1929), p. 660.

[34] *Ibid.*, p. 658.

[35] "Guidebook of the Western United States. Part C. The Santa Fe Route, with a Side Trip to the Grand Canyon of the Colorado," *U.S. Geol. Surv. Bull. 613* (1915), p. 153.

[36] P. 694 of ftn. 33.

[37] P. 46 of ftn. 19.

[38] Carl L. Hubbs and Robert R. Miller, "Mass Hybridization between Two Genera of Cyprinid Fishes in the Mohave Desert, California," *Papers Mich. Acad. Sci., Arts, and Letters* [1942], Vol. XXVIII (1943), pp. 347–48, 376.

River basin, for the genus is well represented in the Colorado fauna and the ancestral stock of *orcuttii* was presumably derived from that basin. However, new data and information now make it seem virtually certain that *G. orcuttii* was recently introduced into Mohave River.[39]

In summary, the theoretical evidence for a once continuous water course between Death Valley and the lower Colorado River basin is good. Structural troughs occur along the hypothetical outlet. Death Valley received water from nearly the entire eastern face of the rugged Sierra Nevada Range, the extensive Amargosa River drainage basin, and the well-watered headwater area of Mohave River, as well as other minor drainages, and presumably the inflow was in excess of evaporation, so that the basin was filled to overflowing. The most logical route for such an overflow was south and east to the lower Colorado River. Mohave River may have alternately discharged into the Death Valley lake and toward the Colorado River, or it may have once directly connected with the Colorado River through a series of lakes east of Barstow. The occurrence of *Cyprinodon* in the Death Valley system demands a connection with the basin of the Colorado River. The presence of a fossil *Cyprinodon* in the region suggests that the connection was an early one, possibly Late Pliocene or Early Pleistocene. If this is true, one would now hardly expect to find anything more than merely suggestive physiographic evidence that a connecting river or river-lake series once existed. The marked distinctiveness of the Recent fish fauna of the Death Valley system from that of surrounding systems also is in harmony with the view that the drainage has been isolated for a long time.

[39] Miller, pp. 111–19 of ftn. 14 (1944).

EXPLANATORY REMARKS ON MAP OF PLEISTOCENE HYDROGRAPHY

The lakes shown on Figure 1 include a number, particularly in southeastern California, that are both pre-Pluvial and post-Pluvial. Lakes Manly, Pahrump, Tecopa, Ward, and Amboy are regarded as pre-Pluvial bodies of water, whereas Lake Cahuilla is of post-Pluvial or Recent age. None of the lakes is believed to be earlier than Pleistocene.

An attempt has been made to trace original sources of information on these waters. The Quaternary lakes as mapped by Russell[40] are shown on later maps by Gilbert,[41] O. E. Meinzer,[42] and W. O. Clark and C. W. Riddell.[43] Meinzer's 1922 map of Pleistocene lakes[44] is the basis of subsequent charts, including the latest map by T. B. Nolan.[45]

All Pleistocene waters are not included, as several mountain lakes were, no doubt, already in existence at that time. Most *playas* probably contained at least shallow and semipermanent lakes. Lakes formed by the desiccation and fragmentation of the larger lakes (such as the separation of Lake Searles, No. 7, into two bodies at a later stage—see text) are omitted. Moreover, not all the lakes shown were contemporaneous, although that impression is given by the map. Hence the picture is greatly simpli-

[40] Ftn. 3, Pl. 1.

[41] Ftn. 2, Pl. 2.

[42] "Geology and Water Resources of Big Smoky, Clayton, and Alkali Spring Valleys, Nevada," *U.S. Geol. Surv. Water-Supply Paper 423* (1917), Fig. 1.

[43] "Exploratory Drilling for Water and Use of Ground Water for Irrigation in Steptoe Valley, Nevada," *U.S. Geol. Surv. Water-Supply Paper 467* (1920), Pl. 3.

[44] Ftn. 4.

[45] "The Basin and Range Province in Utah, Nevada, and California," *U.S. Geol. Surv. Prof. Paper 197-D* (1943), Fig. 11.

fied. Only the major, now disrupted, rivers are mentioned. Others, however, are indicated on the map, following the courses of the Recent streams and definite dry canyons, except where there is contrary geological evidence.

The source of information, from which the outline of each lake named on the map was drawn, is indicated on the facing page. The boundary line of the Death Valley system was compiled largely from the excellent work by Thompson.[46]

[46] Pl. 7 in ftn. 33.

ACKNOWLEDGMENTS.—I wish to express my deep gratitude to three eminent students of desert physiography who kindly gave me the benefit of their knowledge of this former drainage. Dr. Eliot Blackwelder, Mr. Hoyt S. Gale, and Dr. Levi F. Noble were all interviewed and freely offered much helpful advice. Mr. Gale provided an original sketch showing the outlet of Lake Thompson (Fig. 1, No. 19). Financial assistance was received by a research grant from the Horace H. Rackham School of Graduate Studies, University of Michigan. Dr. Carl L. Hubbs made valuable suggestions and read the manuscript. Norman J. Wilimovsky, a student at the University of Michigan, traced the maps.

SPURIOUS LEVELS OF LAKE BONNEVILLE

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ABSTRACT

Investigation of reports of very high shorelines in the Bonneville Basin discloses that no investigated "shoreline" more than 90 feet above the Bonneville level can be attributed to the ancient lake. Checking of evidence upon which these reports were based indicates that a number of confusions and illusions, here described, are responsible.

INTRODUCTION

During a stay of nearly four years in the Utah desert area, numerous high "shorelines" of Lake Bonneville were reported to, or seen by, the writer. Rather thorough investigation of these reported or apparent high shorelines disclosed that there were a large number of shoreline segments, tufa deposits, abandoned beaches, and wave-washed surfaces between the main Bonneville level and about 90 feet above it, but no shore structures reasonably attributable to Lake Bonneville higher than that.

Although a small percentage of the high "shoreline" reports would do credit to the late Baron Munchausen, most of them were undeniably honest and were due to errors of interpretation or observation.

Most of the high "shoreline" reports, it should be noted, are not due to ignorance or stupidity on the part of the observer but are the result of "carrying over" discriminatory habits, of proved merit in most areas, into a region of markedly different observing conditions. Of these observational difficulties, G. K. Gilbert[1] was apparently well aware. In consequence, his report on Lake Bonneville, published in 1890, is still the best general work on ancient lake structures in this area.

[1] *Lake Bonneville* ("U.S. Geol. Surv. Mono.," No. 1) (Washington, 1890).

CONFUSION OF EVIDENCE

Confusion of glacial, nivation, stream, and sheetflood deposits with lake-shore features is common in this area, particularly as these deposits, in many places, merge with lake deposits.

A typical example is the "shoreline" on the southwest side of Deseret Peak (Tooele County), in the Stansbury Range. Here, at an elevation of about 8,000 feet, parts of a long level terrace are covered with boulders, so that the area resembles somewhat an ancient boulder beach, such as the Provo beach on the Stansbury Peninsula, only 30 miles away.

Study of the area indicates that the terrace on the peak is due to structural and stratigraphic control and that the boulders are remnants of the moraine of a small extinct glacier which once occupied a cirque on the southwest slope of the peak.

Confusion of meander and flood deposits with lake-shore debris is quite common; and spurious "shorelines" and "boulder beaches" can be found in the canyons of the Logan, Ogden, Weber, and Provo rivers at several locations. In Big Cottonwood Canyon, near Sandy, Utah, the mixture of lake-shore, stream, and glacial-outwash deposits with weathered fault breccia and disintegrating tillite is so complex as to make certain classification impossible.

In the upper reaches of the Sevier River are a number of old lake beds and deltas, locally attributed to Lake Bonneville. That these are lake features is undeniable; but their hydrographic isolation from the ancient lake, their small areal extent, and their elevation all suggest that they are local features. Field evidence indicates that these deltas and the dividing line between sheetflood stripping and wave-washing is almost impossible to locate *from local evidence alone*. It is also apparent, in some of these areas, such as the south end of Skull Valley, that some of the materials now forming old boulder beaches reached their approximate present locations by flood, rather than wave, transportation.

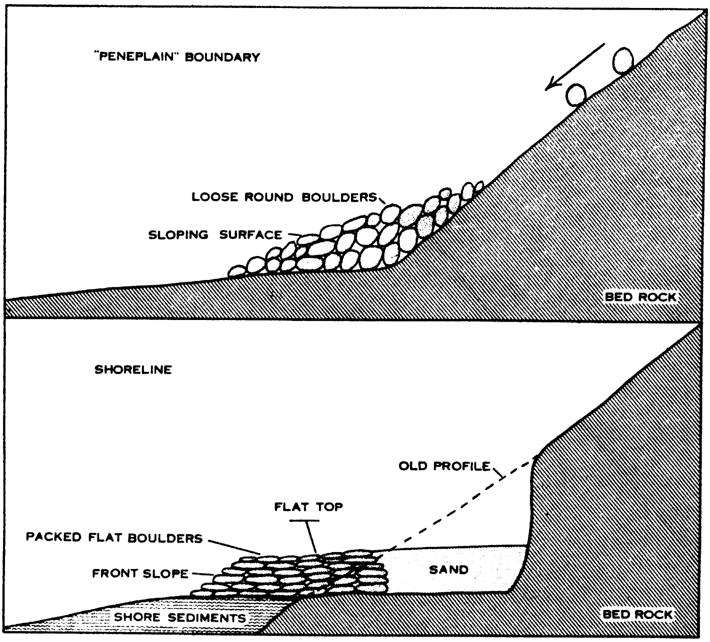

FIG. 1.—Section of a "peneplain" boundary (*upper*) and of a shoreline (*lower*), showing differences in superficial and underlying structure.

other deposits were made in ephemeral lakes or in cutoff meanders. Local causes of deposition are beaver dams, cloudburst dams, fault scarps, and overflowing of natural levees.

Confusion of old wave-washed surfaces with those stripped by sheetflooding is also easy. In some areas, where pediments extend downward into the old lake basin and shorelines are not well developed (as in parts of the Sevier Basin),

Similarity of the boulder deposits in this area, whatever their origin, is notable, particularly in the case of the older deposits, where wind action, desert weathering, and partial burial have modified not only the apparent shape of the deposit but the shapes of the original components.

A number of the reports of high "shorelines" in the Bonneville Basin owe their origin to topographic misinterpreta-

tions, such as the classification of an old erosion surface as a wave-washed surface and of the edge of such a surface as a shoreline. A good example of a pedimental boundary that closely resembles a shoreline is found on the east side of the Stansbury Range (Tooele County), just south of Johnson Pass. Here, a relatively flat shelf extends southward from the pass for about 3 miles. At the upslope margin of the shelf, where the gradient steepens to the mountain slope, are scattered clumps of boulders, faintly resembling an ancient eroded boulder beach. Although this shelf, as a whole, could hardly be mistaken for an ancient shore surface, short sections of it, taken alone, closely resemble poorly developed sections of undeniable shorelines.

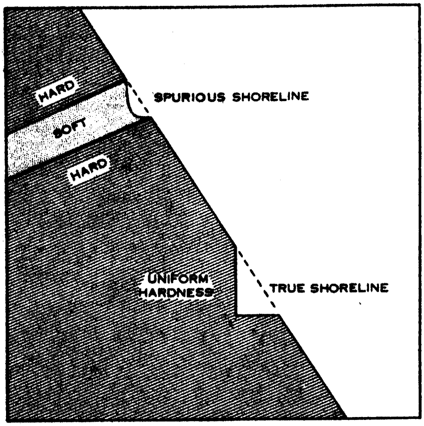

FIG. 2.—Erosion of soft stratum to produce spurious shoreline.

Sections of a so-called "peneplain boundary" and of a shoreline are shown in Figure 1. Although there is a marked superficial resemblance between the two features, they can hardly be confused if carefully studied, even though a considerable part of the evidence has been removed by erosion or buried by sheet-flood deposits.

Where relatively flat-lying strata are

FIG. 3.—The slanting "shoreline" on Simpson Butte, as seen from the air. The true shoreline, of Provo age (*below*), cuts across the local stratification. The spurious shoreline (*above*) exactly parallels the stratification.

exposed in steep slopes in the lake area, softer members of the formation are weathered out, producing shelves which in many instances are reported as shorelines. As some of these cross the actual shorelines, confusion of levels is not only understandable but sometimes very difficult to eliminate.

Differences between the shape of a spurious shoreline due to rock structure and that of a true shoreline are shown diagrammatically in Figure 2. An additional criterion is that no erosional ledge above the ancient lake level is likely to have extensive tufa deposits upon it.

One of the most commonly reported spurious shorelines is the "slanting shoreline" on Simpson Butte (Tooele County). An aerial view of this feature, lighted to emphasize its stratigraphic nature, comprises Figure 3. In this area, whenever a reported shoreline roughly parallels local stratification, particularly if it is inclined or warped, repeated checking is desirable before a lacustral classification is applied.

Several "warped shorelines" in the Cedar Mountains are actually the steep faces of sills, from above which the softer limestone has eroded away.

Confusion of tufa, flowstone, caliche, and sinter leads to many erroneous shoreline reports. Fresh-water tufa deposits and sinter can be distinguished by the contained diatom skeletons. Base-exchange tufa (characteristic of highly saline water), flowstone, and caliche contain few to no diatoms. Chemical tests, in many instances, are necessary to distinguish between base-exchange tufa, flowstone, and caliche.

OBSERVATIONAL DIFFICULTIES

The ancient bed of Lake Bonneville, now a desert, in some places entirely devoid of vegetative cover, is subject to extreme development of mirages, looming, and a "paper-doll' duplication of images, owing to aerial stratification.[2] These optical effects lead to the appearance of spurious shorelines, at certain times of day only, of sufficient clarity to deceive most observers. For reasons not clearly understood, these mirage effects are much more convincing in visual observation than in photographs, although the familiar "water mirage" can be photographed successfully if the exposure is relatively long.

In general, whenever there is a thermal discontinuity in the atmosphere (an inversion is the best known but *not* the only type), there is also an optical discontinuity, the magnitudes of the two phenomena being roughly comparable. Effects of some of these discontinuities are shown in Figure 4. At the top is shown the silhouette of a mountain when the thermal gradient is normal—a condition occurring at night, on cloudy days, and for a short period in the morning. At the center is the appearance of the same mountain when there is a thermal discontinuity close to, or intersecting, the line of sight. This leads to reports of a spurious shoreline on the mountain. At times, the upper part of the view is enlarged, so that the upper part of the mountain overhangs the lower, in which case the optical effect is obvious. At the bottom of Figure 4 is shown the appearance of the same mountain when the line of sight passes through stratified air. Multiple "cutouts" and duplications are common under these conditions.

Elimination of misobservations due to atmospheric optical effects is difficult if only a short time is spent in the area. Repeated observations, at different times of day, or from different viewpoints will usually eliminate these troubles. In

[2] R. L. Ives, "Mirages in the Salt Lake Desert" (in preparation).

most instances, if the position of a distant feature remains constant when it is viewed successively through a polaroid screen, a red filter (Wratten A), and a yellow filter (Wratten K2), it is almost certainly real; but if it either vanishes or changes position as the viewing filter is changed, it is probably spurious and due to mirage effects.

In high altitudes, where the air is quite clear, as is the prevalent condition through much of the year in the Salt Lake Desert, the distance between an observer and a topographic feature can be estimated only with great difficulty. Under certain conditions, not at all uncommon in this area, two hills—one 10 miles from the observer, and the other 30—appear adjacent. As a natural consequence, the shorelines on a near-by hill

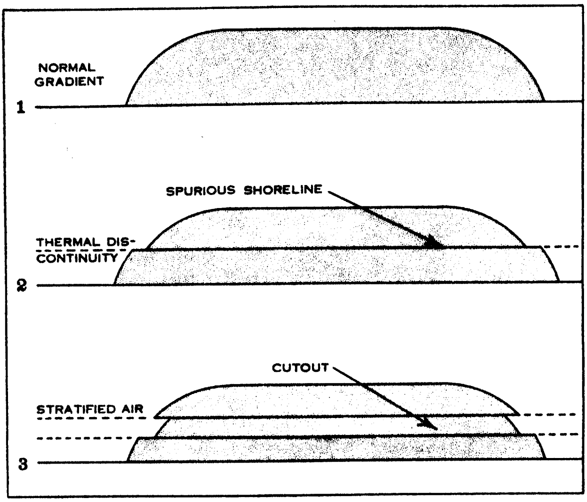

FIG. 4.—Relation of thermal and optical effects to apparent, but spurious, shorelines. *Top*, silhouette of mountain when thermal gradient is normal; *center*, spurious shoreline effect due to thermal discontinuity near line of sight; *bottom*, "cutout" produced by air stratification.

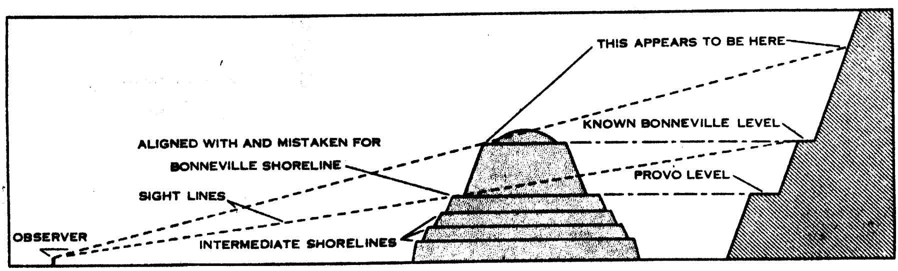

FIG. 5.—Conditions leading to the report of a spurious high shoreline, owing to lack of aerial perspective

may be incorrectly "lined up" with the known features of a more distant mountain range, with the result that a "shoreline" sector, some distance above the Bonneville, is reported on the distant range.

A sketch showing the general conditions leading to a high "shoreline" report when aerial perspective is lacking comprises Figure 5. Although field work, usually involving many miles of travel, is the only method of determining the accuracy of such a report, erroneous observations of this type may be very greatly reduced in number by use of a blue viewing filter, which increases aerial perspective.

CONCLUSIONS

Investigation of high "shoreline" reports from the Salt Lake Desert discloses that no true shorelines more than 90 feet above the Bonneville level can be attributed to the ancient lake; that most of the reports of higher shorelines are honest but mistaken; and that, until improved methods of observation are more widely adopted, reports of high shorelines may be expected to continue.

ACKNOWLEDGMENTS.—The writer is indebted to Colonel John R. Burns for transportation used in checking many of the high "shoreline" reports and to Dr. Carey Croneis for helpful discussions of observing problems and a critical reading of this manuscript.

NOTE ON RECORDING THE ATTITUDE OF STRUCTURAL PLANES

A communication received from Dr. J. A. Broggi, director of the Instituto Geologico del Peru, advocates the desirability of recording the attitude of any structural plane in terms of two numbers, the first giving the azimuth (bearing measured clockwise from true north) of the direction of the dip, and the second its inclination. Thus 40°–25° defines a plane dipping 25° to N. 40° E. (strike is thus N. 50° W.), while 220°–25° defines a plane dipping 25° to S. 40° W. (strike is N. 50° W.). While strike is actually measured in the field in many cases, this is easily converted to direction of dip by taking the strike as an azimuth reading and then adding or subtracting 90°. The latter could be avoided by using a specially graduated dial compass; i.e., one that would read the direction of dip when it was held in the position of the strike. Dr. Broggi advocates this method to simplify note-taking in the field.

REVIEWS

Volcanoes as Landscape Forms. By C. A. COTTON. Christchurch, London: Whitcombe & Tombs Ltd., 1944. Pp. 401; figs. 223. 32*s*. 6*d*.

In the field of geomorphology no name is more widely and properly renowned than that of Professor Cotton. His penetrating analyses of land forms are written in lucid style and attractively illustrated by well-chosen photographs and clean-cut sketches. There is no doubt, therefore, that this, his latest book, will be welcomed by geologists and geographers alike—more than that, being couched in readable form and burdened with few technical terms, it will appeal to any nonspecialist interested in the development of landscapes. Not all forms carved from volcanic rocks are considered; indeed, those produced in late postvolcanic cycles of erosion are omitted from discussion. In brief, focus is centered on volcanic forms little, if at all, modified by denudation.

The book runs to 401 pages, of which the first 69 deal with the mechanism of volcanism, while the rest are devoted almost wholly to morphology. No book of the kind has ever been written before; hence, as the Preface says, "the arrangement is experimental and tentative." Clearly it was this problem and the vexing business of terminology that gave the author his greatest difficulties. Alas, it must be added that his issue from these afflictions was not entirely happy. Before a sculptor starts to chisel, he should know his medium; just so, the reader should know the stuff of which volcanoes are formed before passing on to consider the resultant forms. After summarizing the mechanism of volcanic action, it might have been better, therefore, to describe in detail the products of volcanoes before proceeding to problems of morphology. With that in mind, much of the data presented in later chapters might have been presented earlier, e.g., the pages dealing with lava types and those concerned with such deposits as volcanic mudflows and welded tuffs.

The opening chapter, on "Types of Eruption," might profitably have been expanded. While the time-honored classification into Hawaiian, Strombolian, Vulcanian, etc., types is adopted, its shortcomings are properly mentioned. Neither here nor elsewhere in the book is the treatment dogmatic. Some may feel, however, that too much emphasis is laid on the chemical composition of the magma in determining the type of activity, and too little on the temperature, gas content, degree of crystallization and depth of the magma chamber. Incidentally, the term "Plinian eruption" has been used in such widely different senses by various writers that it has come to have little meaning other than to signify catastrophic explosion following a long period of quiescence. It would seem wise, however, to exclude from the category all "ultra-Vulcanian" eruptions in which only old, lithic debris is expelled, for the eruption which Pliny described involved mainly the discharge of fresh magma as pumice and scoria from the feeding chamber of Vesuvius.

In chapters ii and iv, on "Lava Volcanoes," an excellent account is given of the Hawaiian type of activity, based mainly on the lifelong studies by Jaggar. It is welcome to see full recognition made of the extremely complex feeding mechanism of Hawaiian volcanoes, of the importance of rifting, and of the subterranean pulsing of magma that continually makes Hawaiian volcanoes tumesce and subside as if they breathe. Welcome, also, is the introduction of Jaggar's terms "pyromagma" for the free-flowing, often foaming, lighter magma that grades downward into the relatively immobile "hypomagma," with its gas chiefly or wholly in solution; and the usage of "bench magma" and of "epimagma" for the degassed, inflated pyromagma. Without recognition of these various forms, the mechanism of Hawaiian volcanoes cannot rightly be understood.

Chapter iii includes a résumé of ideas developed at the Kilauean lava lake by Jaggar, Day, Shepherd, and others relative to the heating of lava by reactions between escaping gases and by the combustion that attends engulfment of the walls of the lake. Some may question whether heat derived by such processes is enough to offset the cooling caused by gas expansion. Perhaps too much insistence has been placed on the observations at Kilauea; for the conditions that obtain in an open lava lake with strong convective circulation are very different from those that prevail in most of the active

volcanoes of the world. It may also be that the importance of gas-fluxing in reopening volcanic conduits after periods of dormancy has been overemphasized. One wonders whether or not, in a work devoted primarily to landscapes, such debatable topics merit more than passing mention.

Chapter v deals with "Pumice Volcanoes"; but the heading, like several others in the book, is misleading, for here Professor Cotton includes discussion of the temperature and source of magmas and the origin of magmatic gases, and he is concerned not merely with volcanoes that erupt pumice, as that term is generally understood, but with explosive volcanoes in general. In reference to the temperatures of the more siliceous lavas the suggestion is made that the presence of tridymite and cristobalite among the final products of crystallization may indicate temperatures in the vicinity of 1,500° C. and that some such temperature may be required to make these siliceous lavas flow freely! True, reference is added in a footnote to low-temperature "pneumatolytic" cristobalite, but the idea that a siliceous lava could perhaps approach complete solidification at temperatures approximating 1,500° C. is quite erroneous. Temperatures between 600° and 900° C. are normal for siliceous flows. Many other questions jump to mind in reading this chapter. Does the effervescence of a magma tend to raise its temperature? How important is the content of ferrous iron in controlling the viscosity and determining thereby the type of discharge? Is it as critical as temperature or the vapor pressure of the still-liquid fraction of the magma about to escape?

Discussion of the source of magmas is brief and based chiefly on the latest opinions. Unfortunately, or so it seems to the reviewer, most space is given to Van Bemmelen's conception that "volcanic activity on the top of orogenic uplifts is caused by palingenetic, hybridic, or syntectic magmas. These magmas are saturated with emanations and this explains the high explosiveness." Perhaps granite batholiths do originate by metasomatic alteration of the roots of mountains, but to relate "granitization" to volcanism is to overtax credulity. Most batholiths consist of granite, and most volcanoes, even in orogenic belts, erupt basalt; and these facts alone should give cause to doubt an intimate connection between them. Moreover, the geological record shows that submarine discharge of pillow basalt and injection of serpentine usually precede orogeny, that batholithic invasion mainly follows folding and causes mountain-uplift, and that most volcanism begins at a much later date. The view of Kennedy and Anderson, referred to by Professor Cotton, that batholiths originate at the expense of the sial and that volcanoes are fed from underlying layers of tholeiitic and olivine basalt seems deserving of much wider recognition. The ensuing pages, dealing with revival of activity after dormancy, by gas-fluxing of plugs and by retrograde boiling of magma, present a summary of the ideas of Morey and Rittmann.

Chapter vi, devoted principally to Vesuvius and its cycle of activity, embodies a clear account of the theories of Perret and Rittmann. So many complex factors determine the types of volcanic eruption, and a single volcano emitting magma of uniform composition may behave in such a bewildering variety of ways, that one hesitates to accept the suggestion that differences between the behavior of Hawaiian and Vesuvian volcanoes may be related to minor differences in the chemical composition of their magmas.

Part II, the main portion of the book, is an extremely able study of volcanic landscapes, and it shows that the author has kept closely in touch with recent literature. It begins with an account of "Domes and Cones of Basaltic Lava." Characteristic of domes are the broad and gently sloping volcanoes of Hawaii, often referred to by others as "shield volcanoes." Their inner structure and mode of growth are clearly explained. Most of them are shaped like overturned spoons or canoes, in contrast to the steeper basaltic cones (shields) of Iceland, the outlines of which are approximately circular, since they grow entirely by overflow from the summit vents and are not augmented, like the volcanoes of Hawaii, by repeated discharge from fissures on the flanks.

The next three chapters are mainly concerned with basaltic lava plateaus, the surface features of basaltic flows, and the fragmental ejecta of basaltic volcanoes. These forms are then contrasted with those developed by eruption of viscous and more siliceous lavas that pile over the vents as steep-sided cumulo domes or tholoids, like that capping Mont Pelé, or are forced upward, piston-like, to produce plug domes, such as Lassen Peak.

Particularly good is the chapter describing "Ash Showers and *nuées ardentes*." For the first time in any textbook, one finds full dis-

cussion of the various kinds of *nuées*, not only those such as were discharged by Mont Pelé and the Soufrière of St. Vincent and those produced by the crumbling of domes, as in Java, but also those erupted from swarms of fissures, as near Katmai in 1912. Professor Cotton's insistence on such fissure eruptions of pyroclastic ejecta is not surprising when one recalls that in the North Island of New Zealand welded tuffs cover approximately 10,000 square miles, locally to depths of several hundreds of feet. Doubtless many other extensive rhyolitic plateaus, long thought to consist of lava flows, will prove, on further examination, to be made of similar, fissure-erupted tuffs. The author's experience in New Zealand has also led him to stress a fact not often noted, namely, that some of the most violent explosive eruptions from central vents fail to produce large cones but instead leave widespread blankets of pumice and ash. Two possible causes of such "coneless showers" are mentioned; a third may be added, namely, a shallow explosion focus which tends to give wide scatter to the ejecta.

Very likely, the most voluminous explosive eruption of historic times was that of Tamboro, on the Island of Sumbawa, in 1815. Verbeek's estimate that no less than 150 cu. km. of material were discharged has been handed down from one text to another ever since, though as Van Rheden has demonstrated, the estimate is approximately five times too large. Indeed, it seems safe to say that within historic times no volcano has discharged more than 50 cu. km. of material in a single explosive cycle.

The next chapter, on "Ash-built and Stratified Cones" is another unusually good discussion, rich in up-to-date material. Reference is made, for instance, to a feature too little realized, namely, the phenomenally rapid growth possible in ash cones and pumice cones. In 1937, the cone of Vulcan, in New Britain, rose to a height of 600 feet during its first day; within three or four days it was 742 feet high. The Mexican volcano Paricutin rose to 1,100 feet in the first ten weeks. Here, also, one finds well-merited space given to another topic generally slighted, namely, "volcanic mudflows." Especially in tropical regions and among snow- and ice-capped cones, the mingling of loose ejecta with water produces slurries of mud, heavily charged with boulders, that spread for vast distances; and many of the coarse deposits found in ancient volcanic regions are clearly of this origin. Professor Cotton, aware that "mudflow" is a misnomer as applied to such materials, has had the courage to introduce an alternative term long familiar to volcanologists, the Javanese word "lahar." Doubtless, some will raise objections, as others did to the Hawaiian names "aa" and "pahoehoe," but this reviewer hopes that "lahar" has come to stay and will gain a wide acceptance.

In describing "Maars and Tuff Rings," a brand-new word, "ubehebe," is invented for volcanic embryos or "maars" devoid of water. The name comes from the Ubehebe craters in Death Valley, a series of at least five (not two) basins produced by explosions of basaltic scoria mixed with sedimentary debris. It seems adequate, however, to call such depressions, bordered by low rims of fragmental ejecta, simply "explosion pits."

Space is also allotted to descriptions of meteor craters and to cryptovolcanoes, like the Steinheim Basin and the Rieskessel of Germany and the ring structures lately studied in this country by Bucher.

Following a brief account of submarine eruptions and pillow lavas comes the longest chapter in the book, devoted to "Craters and Calderas; Volcanic Depressions and Lakes." Here, again, is a wealth of up-to-date information. Collapse, rather than explosive decapitation, of cones is properly considered as the prime cause of calderas, engulfment resulting chiefly from hurried drainage of magma from beneath the tops of volcanoes either by colossal discharge of ash and pumice, as at Krakatoa, Crater Lake, and Monte Somma; by rapid outflow of fluid lava from the lower flanks, as in Hawaiian volcanoes; or by subterranean migration of magma. Van Bemmelen's view that formidable arcuate rents have developed on Javanese volcanoes by downsliding of portions of overloaded cones resting on a weak, inclined floor is described; and the manner in which sectors of cones may collapse to form eccentric depressions like the Val del Bove on Etna is noted. Especially noteworthy are the pages discussing the largest volcanic depressions of all (now, for the first time, finding place in a general text), namely, volcano-tectonic depressions. These form by downbending and faulting along tectonic lines following tremendous outwellings of rhyolitic ash from swarms of fissures. In other words, they are related to great sheets of welded tuff (ignimbrite), like those along the Barisan Rift of Sumatra and in the North Island of New Zealand. A particular example is

the basin, 100 km. long and 31 km. across, that holds Lake Toba.

The book ends with treatment of the erosion of volcanic landscapes, first telling of the denudation of basalt and ignimbrite plateaus and of basaltic plains, both by rivers and glaciers, and concluding with an account of the destruction of volcanic mountains and the erosion cycle as applied to calderas. Knowing Professor Cotton's unusual skill in analyzing stages of erosion, one would have been glad to see this discussion carried further.

The book is effectively illustrated by 138 line-drawings and 85 photographs. Fifteen of the latter are excellent aerial views that whet the appetite for more. Great care has been exercised in preparing the Index, and the proofreading throughout has been done so thoroughly that a misprint is as hard to find as a needle in a haystack. Oddly enough, the only slips noted occur together in the caption under Figure 186, where steptoes surrounded by basaltic lava are said to be composed of granitic terrain, though they are really islands of basaltic scoria, and the locality is not in Washington but in Oregon.

If anyone wishes to gain a comprehensive and balanced picture of current views concerning volcanoes, this is the book for him. Few will gainsay that it is by far the best general discussion of volcanoes that has yet appeared in English in textbook form.

HOWEL WILLIAMS

Tectonic Map of the United States. Prepared under the direction of the COMMITTEE ON TECTONICS, DIVISION OF GEOLOGY AND GEOGRAPHY, NATIONAL RESEARCH COUNCIL, CHESTER R. LONGWELL, Chairman. Tulsa, Okla.: American Association of Petroleum Geologists, 1944. Scale 1:2,500,000, or 1 inch = 40 miles. Printed in 7 colors, on 2 sheets; full map, size about 80 × 50 inches. $2.00 rolled in mailing tube; $1.75 folded in manila envelope; $1.50 in lots of 25 or more, rolled or folded.

The much-needed, long-desired tectonic map of the United States has at last appeared. Conceived at the initial meeting of the Committee on Tectonics in 1922, the project passed through a slow period of gestation, during which ideas and plans took shape. Active assembling of the data began in 1934, when the country was divided into eleven "tectonic districts" and each member of the committee assumed responsibility for one district. Later, the number was increased to fourteen, including one in southeastern Ontario. Added also were adjacent parts of Mexico for which abundant data were available.

A full explanatory statement of the development of the project, the techniques for delineating the various structures, the representation in color of kinds and ages of bedrock in certain large areal units, together with other pertinent information, has recently appeared in the *Bulletin of the American Association of Petroleum Geologists*, Vol. XXVIII (1944), pp. 1767–74, under the title "Tectonic Map of the United States," by Chester R. Longwell.

The material compiled by the members of the committee was co-ordinated and prepared for drafting by Philip B. King, vice-chairman of the committee, to whom much credit is due for the final consummation of the map. Early in 1940 about two hundred lithoprinted copies of a preliminary black-and-white edition of the map, drafted under the direction of G. W. Stose, of the United States Geological Survey, were distributed to organizations and individuals throughout the country, with requests for corrections of errors, suggestions of desirable changes, and additional data. Benefiting from this careful scrutiny, the completed map should now represent the structural features of the United States and some adjoining areas about as authoritatively as is possible with present knowledge.

The scale being identical with that of the *Geological Map of the United States* issued by the United States Geological Survey in 1932, the two maps can readily be used to supplement each other. The manifold different structures are clearly and effectively depicted, making the new map extremely useful for structural studies of all sorts, and especially those of broad regional scope.

R. T. C.

UNITED STATES GEOLOGICAL SURVEY STAFF CHANGES ANNOUNCED

Director W. E. Wrather, of the United States Geological Survey, has announced recent organizational changes within the Geologic Branch of the Survey, which is headed by Chief Geologist W. H. Bradley.

The Geologic Branch has been subdivided into two divisions and a technical service and administrative group. Dr. H. M. Bannerman has been named chief of the Division of Economic Geology. During most of the war period he served as chief of the Section of Nonmetallic Minerals.

Dr. H. S. Ladd has been designated chief of the Division of Areal Geology and Basic Sciences. He was formerly regional geologist, in charge of the Rolla, Missouri, office of the Survey. Dr. J. W. Peoples, assistant chief geologist, has been named head of the Technical and Administrative Group.

A special research staff has been set up within the Geologic Branch, having advisory functions in connection with long-range research planning and Branch policies. This staff includes Drs. D. F. Hewett, G. F. Loughlin, and W. W. Rubey. Other geologists are temporarily assigned to this staff as the planning needs dictate.

A new Section of Geologic Information and Reports has been established. Don L. Carroll, until recently foreign editor and staff geologist of the *Oil Weekly*, has been designated chief of the new section.

The following sections now comprise the Division of Economic Geology:

Geology of Fuels, H. D. MISER, *Chief*
Geology of Metalliferous Deposits, CHARLES F. PAR[illegible] JR., *Chief*
Geology of Nonmetalliferous Deposits, JOSIAH BRI[illegible] *Acting Chief*
Foreign Geology, J. V. N. DORR, II, *Acting Chief*

Within the Division of Areal Geology and Basic Sciences are included the following sections:

Areal Geology, J. T. HACK, *Acting Chief*
Engineering Geology, E. C. ECKEL, *Chief*
Chemistry and Physics, W. T. SCHALLER, *Chief*
Paleontology and Stratigraphy, J. B. REESIDE, JR., *Chief*
Petrology, C. S. ROSS, *Chief*
Military Geology, E. S. LARSEN, III, *Acting Chief*
Geophysics, J. R. BALSLEY, *Acting Chief*

The Technical Service and Administrative Group includes the following units:

Manuscript Review Board, C. H. DANE, *Chairman*
Geologic Map Editor, E. N. GODDARD
Geologic Cartography, L. B. PUSEY, *Chief*
Committee on Geologic Names, MISS FRA[illegible]ES WILLOUGHBY, *Secretary*
Office of the Chief Clerk, MRS. A. L. BR[illegible]WN, *Chief*

Changes in field assignments have also been announced. A. L. Weissenborn, of the Rolla, Missouri, office, has been designated as regional geologist at Spokane, Washington. Robert A. Laurence has been made eastern regional geologist with temporary headquarters at Jefferson City, Tennessee. Charles B. Hunt, formerly chief of the Military Geology Unit, has been designated regional geologist at Salt Lake City.

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THE TOURMALINE GROUP IN SEDIMENTS

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ABSTRACT

Tourmaline is really a complex isomorphous mineral group which can be easily differentiated under the microscope into a series of varieties and types. These types are based upon the recognition of five main sources of tourmaline in sediments: granitic, pegmatitic, metamorphic injected, sedimentary authigenic, and reworked sedimentary detrital.

Actual examples of the application of these concepts to the solution of problems of correlation, interpretation, and differentiation of sediments and to the reconstruction of paleogeographic conditions are given.

INTRODUCTION

Tourmaline is one of the most widespread nonopaque heavy accessory constituents in sediments. It shares first place with zircon as the most abundant and most frequently found heavy mineral.

Tourmaline occurs in sediments of all types and of all ages. This wide distribution has resulted in tourmaline being taken for granted by many students of sediments who considered it as a mineral of no particular genetic or stratigraphic significance. However, precisely the reverse is true. This is due to the fact that tourmaline is not a simple—or single—mineral species but rather a complex isomorphous group, with an extremely elastic formula and possessing a series of very sensitive morphological characteristics which reflect very closely both the ontogeny and the phylogeny of each grain and thus can act as excellent guides to the origin and history of each tourmaline grain and consequently of the sediment in which these grains are found. As a result, tourmaline can be used effectively as a guide mineral in the solution of paleogeographic and stratigraphic problems.

GENERAL CHARACTER

Tourmaline is a complex aluminosilicate of boron with a variable formula in which considerable replacement and proxying takes place. Specific gravity averages around 3.1; hardness, around 7.5. Tourmaline is hexagonal and optically negative. The normal habit is prismatic, terminated with asymmetrical pyramids. There is practically no cleavage, but in some grains a rude basal parting is present. The prisms may show a trigonal cross section with pseudocurved sides.

Tourmaline is ultra-stable, both chemically and mechanically. It is possibly the most wear-resistant of all common

minerals. According to F. W. Freise,[1] its resistance coefficient to abrasion is from 850 to 950, as against 510 for chalcedony, 245 for quartz, and 150 for orthoclase.

CHEMICAL COMPOSITION, COLOR, AND OPTICAL PROPERTIES

The generalized formula of tourmaline may be written, after F. J. Pettijohn and W. C. Krumbein,[2] thus: (Na, Ca) $R_3(Al, Fe)_6B_3Si_6O_{27}(O, OH, F)_4$, where R = Mg, Fe″, Fe‴, Al, Li, Mn, and Cr.

According to N. H. and A. N. Winchell,[3] the three basic focal points of the tourmaline group are:

Elbaite, or lithium tourmaline:
$H_5NaLi_2Al_2Al_8B_4Si_8O_{41}$

Schorlite, or iron tourmaline:
$H_5NaFe_2Fe_2Al_8B_4Si_8O_{41}$

Dravite, or magnesium tourmaline:
$H_5NaMg_2Mg_2Al_8B_4Si_8O_{41}$

The situation is complicated by the fact that, in addition to changes in R, there are possible wide fluctuations in the basic formula between Na and Ca and between Al and Fe. As a result of these changes, tourmaline shows considerable differences in color and, to a minor extent, in specific gravity and refractive indices. For instance, elbaite may be deep blue (indicolite) if Na predominates, or pink (rubellite) if Li predominates; dravite is normally(?) colorless if Ca exceeds Na but may become bluish if Na exceeds Ca, or greenish, brown, or black, depending upon the relative amounts of Fe″ and Fe‴.

Furthermore, to make matters even more complex, tourmaline may be zoned (radially or along *C*-axis), forming the so-called "watermelon" varieties. This zoning (most commonly red inside, green outside) is easily visible in light-colored hand specimens but may also be present in dark crystals which megascopically appear to be black throughout but give, upon crushing, a blue and a green tourmaline, each with somewhat different optical properties. Under the microscope the usual varicolored tourmaline shows both yellow and blue colors within the same grain, this being a diagnostic feature for correlation purposes. The specific gravity, color, and indices are lowest for the pure-magnesium tourmaline (dravite) and increase gradually with the appearance of Li, Mn, etc., and especially Fe.

The grouping of tourmaline varieties as shown in Table 1 has been worked out from the data of E. S. Larsen and H. Berman,[4] the Winchells,[5] and Dana R. Russell.[6] There is some overlapping, and considerably more study will be required to delineate these types properly and evolve a final classification. The indices are so close that they require determination with immersion oils. For rapid work in Canada-balsam mounts the indices are of little use, and all classification must be made on the basis of color alone.

Tourmaline (pure Ca-Mg varieties excepted) has a very strong *pleochroism*, with $Z > X$. The pleochroic formula is:

[1] "Untersuchung von Mineralien auf Abnutzbarkeit bei Verfractung im Wasser," *Tschermaks min. u. petrog. Mitt.*, N.S., Vol. XLI (1931), pp. 1–7.

[2] *Manual of Sedimentary Petrography* (New York: Appleton, 1938), p. 452.

[3] *Elements of Optical Mineralogy* (New York: John Wiley, 1931), Part II, "Description of Minerals."

[4] "The Microscopic Determination of the Nonopaque Minerals," *U.S. Geol. Surv. Bull. 848* (1934), p. 247.

[5] See pp. 246–48 of ftn. 3.

[6] "Tables for the Determination of Detrital Minerals," *Rept. Comm. on Sed. 1942, Nat. Res. Counc.*, pp. 6–9 and chart.

Z	X
1. Yellow	1. Colorless
2. Brown	2. Yellow
3. Green	3. Pale brown, pale pink
4. Deep pink	4. Pale pink or colorless
5. Blue	5. Mauve, lavender, or violet
6. Black	6. Brown

The maximum absorption ($Z \perp c$) is visible when the tourmaline prism is parallel to the horizontal cross-hair of the microscope (i.e., elongation perpendicular to vibration plane of the polarizer as built in most American and German microscopes). However, because of the occurrence of basal parting, an abnormal positive elongation may occur ($Z \parallel$ basal parting, and hence $\parallel$ elongation of pseudo-prismatic fragment) which naturally reverses the apparent pleochroic formula. This does not happen very frequently but has been known to mislead beginners into confusing tourmaline with biotite.

The birefringence of tourmaline is rather high: 0.015–0.035. This is the interference value for a standard 0.03 mm. thin section, with 0.025 as a good average; but in loose grains found in heavy residues, owing to the prevalence of the basal parting, there are so many near-basal sections (which are also non-pleochroic) that the observed interference value of tourmaline may be much less. As a result, it is not difficult to confuse in thick grains the apparent birefringence of basal sections of tourmaline with that of prismatic sections of other minerals (such as andalusite) with a much lower birefringence.

The *maximum* interference color for 0.09 mm. (i.e., very fine sand grains, or the average material caught on the 230-mesh sieve) is in the third order and for 0.18 mm. (fine sand fraction or the 120-mesh sieve material) is in the higher

TABLE 1*

COMPOSITION AND PROPERTIES OF THE TOURMALINE GROUP

	Sp. Gr.	ϵ	ω
Colorless tourmaline (pure Na *dravite*)	2.98–3.04	1.613	1.636
Colorless tourmaline (pure Ca-Mg *urite*)	3.05	1.621	1.641
Pink tourmaline (Li *rubellite*)	3.02–3.14	1.624	1.645
Blue tourmaline (*Na*-Fe-Li *indicolite*)	3.09	1.630	1.660
Green tourmaline (Ca-Na-Fe-Li *elbaite* or *schorlite*)	3.10	1.624 1.645	1.635 1.670
Brown tourmaline (*Fe dravite* or *Mg*-Fe *schorlite*)	3.10	1.633 1.640	1.653 1.670
Deep brown to black tourmaline *Fe* schorlite)	Up to 3.24	Up to 1.658	Up to 1.698
Deep pistachio-green tourmaline (Cr tourmaline)	3.3	1 641	1.687

* Bn normally between 0.015 and 0.035 for 0.03 mm. thickness.

orders. As said before, in basal sections these amounts are much less.

GRAIN MORPHOLOGY

In addition to color, relief, and birefringence, which depend upon chemical composition, tourmaline shows considerable variations in its morphology (both external and internal), depending upon the conditions of its genesis. The following physical characteristics are easily observable and may be of great diagnostic importance in tracing the origin and history of each grain:

1. *Size.*—Small prisms versus large prisms versus fragments of still larger prisms. Large crystals do not survive in sediments in one piece, and hence the abundance in a sediment of large tourmaline fragments is evidence of still larger crystals within the source area.

2. *Shape and roundness.*—Since tourmaline is extremely resistant to wear, it is quite common to find in one sediment, owing to mixing from several source areas, a collection of tourmaline grains in different stages of modification (rounding). Shape may range from original prismatic (idiomorphic) to perfectly rounded (globular), with angular fragments and subrounded prisms or fragments in between. Rounded grains may be refractured during a later cycle of abrasion.

The study of basal parting (i.e., primary versus clastically produced elongation) belongs here.

3. *Inclusions.*—Common in tourmaline and may be highly diagnostic of its provenance. These inclusions may be: (*a*) cavities (empty vacuoles or bubbles, frequently with colored walls); (*b*) microlites of rutile (common), magnetite, zircon, cassiterite, topaz, fluorite, quartz, feldspar(?), muscovite, anatase, brookite, and titanite; and (*c*) carbonaceous particles (locally abundant).

ORIGIN AND PARAGENESIS OF TOURMALINE

Five main types of large-scale provenance are possible for tourmaline (Fig. 1):

1. *Granitic tourmaline.*—Formed as an end-phase product within large plutonic igneous bodies. Typical morphology is small or medium-sized idiomorphic crystals, frequently full of bubbles and cavities. This may suggest deuteric replacement. Typical color is dark brown, green, or pink (with a greenish cast) suggesting a possible Fe composition with Li(±). A typical specimen is shown in Figure 2 (*2b*).

2. *Pegmatitic tourmaline.*—From pegmatites and vein rocks. Typical habit is that of *very large crystals* (hence occurs in sediments as angular fragments as shown in Fig. 2 [*2a*]). Typical color is *blue*, with pleochroism in shades of mauve and lavender; composition is Na with some Li. Other varieties are possible but are less typical. Inclusions are rare.

3. *Tourmaline from pegmatized injected metamorphic terranes.*—Habit and color are variable and, to a very large extent, are related to the petrography of the host rock and apparently to its texture, porosity, and permeability.

In pegmatized sandstones (and hence in metaquartzites, quartz-schists, and quartz-mica-schists) the morphology of tourmaline is variable. Sometimes almost the same types occur as in granites (brown and pinkish, less commonly green). In other, more common, instances the tourmaline crystals are pale to deep brown and generally are poor in inclusions. Their size, as a rule, is smaller

than that of granitic tourmaline (Fig. 2 [*2c* and *2d*]).

In slates, phyllites, and nonquartzose mica-schists the typical morphology is *very small idiomorphic* crystals, frequently full of *black carbonaceous* inclusions. These carbonaceous inclusions occur only if the injected phyllite was originally a dark or black shale. Such carbonaceous inclusions, as is generally known, are also common in andalusite and staurolite. Color is colorless to very pale (or less commonly deeper) brown. Composition is MgFe. Possibly, the very pale color in some tourmalinized phyllites may be due to a selective adsorption or absorption effect by the host rock on the Fe in the pegmatitic juices. Complications occur; for instance, a metamorphic terrane consisting of alternating layers of quartz-mica-schist (old sandstone) and mica-schist (old shale) may in some cases show both types of tourmaline (pale and deep colored), alternating layer by layer, possibly even foot by foot, with the darker tourmaline present in the more permeable layer (quartz schist, former sandstone). During igneous tourmalinization of sediments and metamorphic rocks the tourmaline may occur either as overgrowths (very rare) or more commonly as newly formed crystals with no visible nuclei. The overgrowths are extremely rare, because at high temperatures an almost total reorganization of the nucleus is likely to take place. Furthermore, almost all of the tourmaline in injected terranes is new, having been formed *de novo* without the aid of pre-existing nuclei.

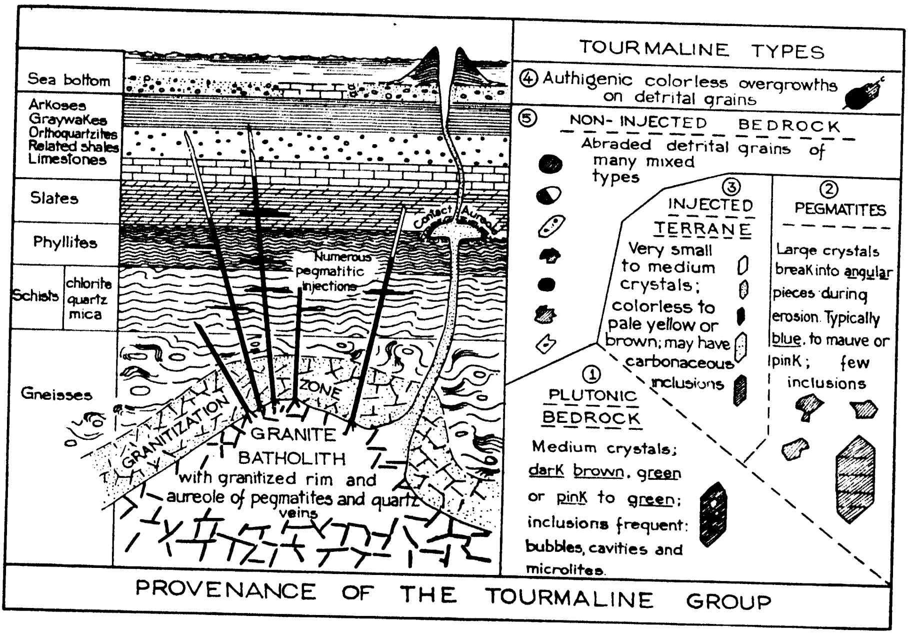

FIG. 1.—Provenance of the tourmaline group, showing distribution of the tourmaline types according to depth or intensity of diastrophism (roughly equivalent to depth).

4. *Sedimentary authigenic tourmaline*

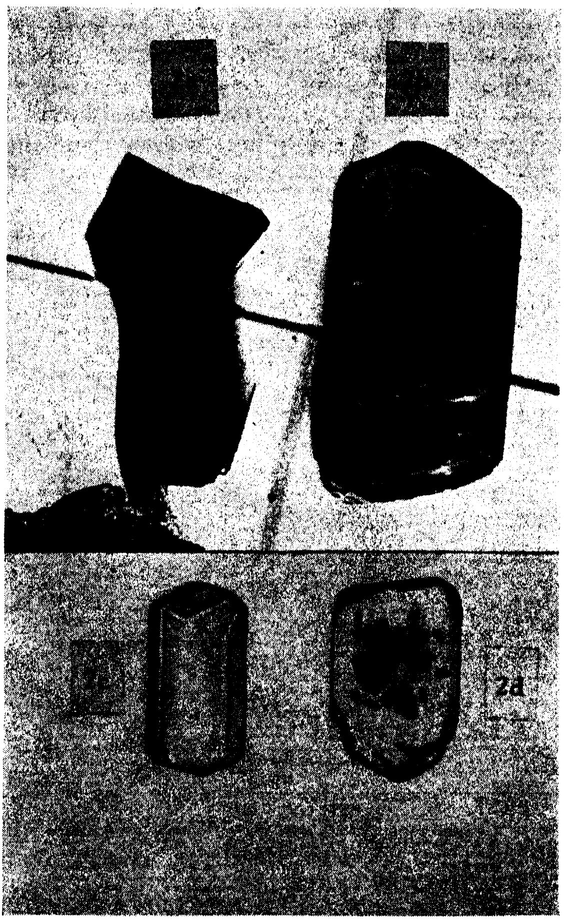

FIG. 2.—High-temperature tourmaline varieties; all magnifications 140×.

2a) Pegmatitic tourmaline (Type 2 of Fig. 1): fragment from large blue crystal. From Triassic of Connecticut; primary occurrence is in pegmatitic sills near Middletown.

2b) Plutonic tourmaline (Type 1 of Fig. 1): brown idiomorphic crystal full of inclusions. From Triassic of Connecticut; primary occurrence is in granite stocks of east-central Connecticut.

2c) Injected terrane-type tourmaline (Type 3 of Fig. 1): small colorless idiomorphic crystal. From Hartland schist, Connecticut.

2d) Same as *2c*, but faintly yellow and with carbonaceous inclusions.

(cold water) formed at bottom of sea penecontemporaneously with the including sediment.—Typical morphology is that of overgrowths which show polar development at one end only of the *c*-axis. According to Stella W. Alty's[7] pyroelectric tests, these overgrowths are restricted to the antilogous pole, which is characterized crystallographically by the faces *r* $(10\bar{1}1)$ and *m* $(10\bar{1}0)$.

Typically, these overgrowths are colorless to very very pale blue, indicating a Mg composition, with possibly some Ca or Na. Their refractive indices are very low. According to Alty for Michigan species, $\omega = 1.628$ and $\epsilon = 1.610$; and according to P. D. Krynine and O. F. Tuttle[8] for central Pennsylvania varieties, $\omega = 1.630 \pm 2$ and $\epsilon = 1.612 \pm 2$. These indices are even lower than those of the purest high-temperature dravite or urite described in the mineralogical literature.

These overgrowths (Fig. 3) are generally small, ranging from 5 to 25 per cent of the size of the nucleus; but they may become very large, reaching 50, 100, or even 200 per cent of the nucleus. In absolute figures the largest overgrowths seen by the writer reached 0.25 mm. in length.

The overgrowths are identical in their properties throughout the same formation, but the nuclei naturally are different. Hence, colorless (Mg) overgrowths may develop on brown, blue, green, yellow, or black cores, all of which have different chemical compositions. Between the overgrowth and the nucleus is found a zone of "roots," or reorganization, where the core and the outgrowth are welded together. This zone of roots (Fig. 3 [*3d* and *3f*]) is characterized by pitting and etching of the nucleus, with roots of the outgrowth entering these pits. The composition of this pitted root zone is apparently intermediate between that of the overgrowths and that of the nucleus. If the overgrowth is broken off, this pitted surface remains at the antilogous pole as evidence of its former existence. The overgrowth may contain inclusions, engulfed during its period of growth (Fig. 3 [*3e*]).

Pseudo-overgrowths which can be mistaken for authigenic tourmaline by overenthusiastic observers can occur in two ways:

a) Tourmaline grains may be fractured and abraded at one end in such a way as to produce thinning of the grain (which may render the thinned portion almost colorless) and also to produce some sort of crystal outline along incipient partings parallel to the original prismatic faces of the grain. This, in some cases, may give the impression of an overgrowth upon casual examination.

b) In rocks which are cemented by a mixture of secondary quartz and recrystallized micas, such as illite or sericite (the so-called *Quartz-Glimmer Zement* of the German petrographers), the cementing material may adhere to the grains upon crushing of the rocks (other cements usually do not do this). These particles of cement form irregular pale-bluish wisps rather similar to authigenic tourmaline overgrowths, especially if the central cores are dark. However, these wisps are not in optical continuity with the nucleus.

Authigenic tourmaline is a typical sedimentary development, comparable

[7] "Some Properties of Authigenic Tourmaline from Lower Devonian Sediments," *Amer. Min.*, Vol. XVIII (1933), pp. 351–55.

[8] "Bellefonte Sandstone: Example of Tectonic Sedimentation" (abstract), *Bull. Geol. Soc. Amer.*, Vol. LII (1941), p. 1918.

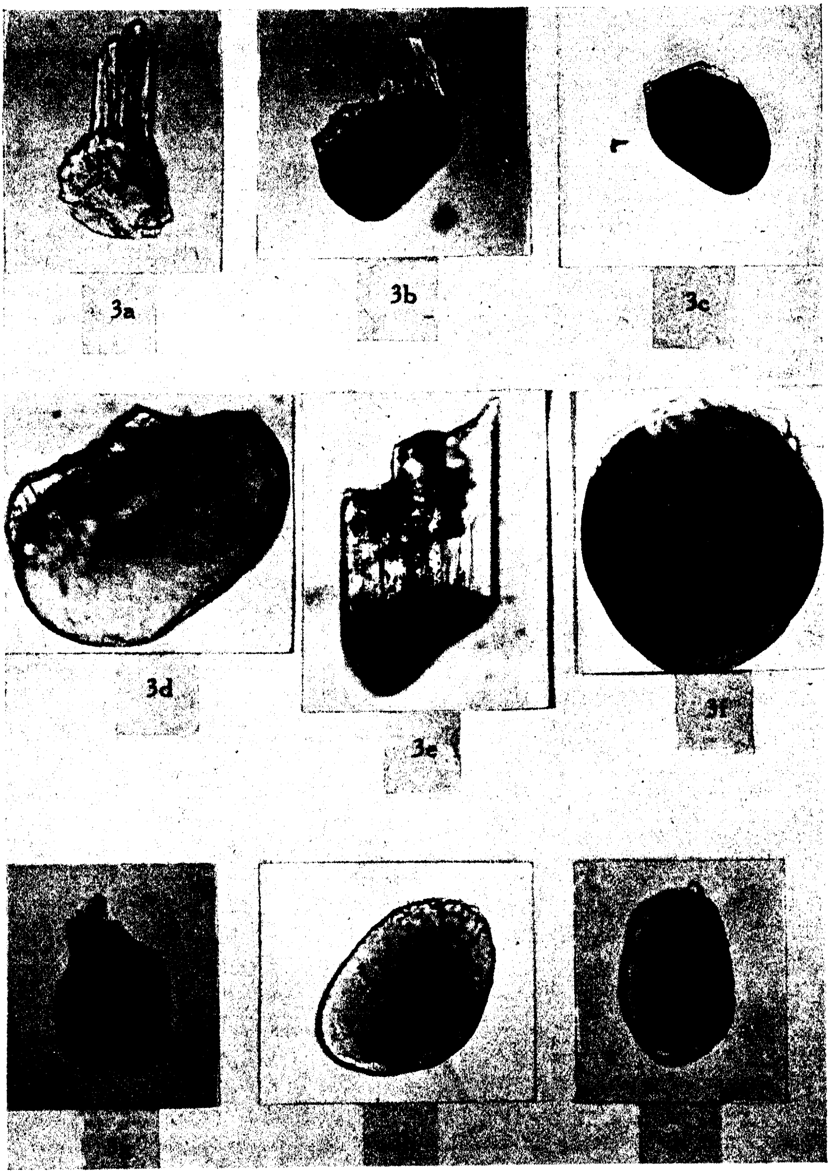

FIG. 3.—Legend on facing page

to the Clinton iron ores or other sedimentary minerals. It is usually restricted to relatively thin stratigraphic horizons, but geographically it may cover areas well in excess of 50,000 square miles. The occurrence within the same formation takes place regardless of the changes in permeability or cementation of the formation and is present even in completely welded, early cemented orthoquartzites or nonporous calcareous sandstones, thus establishing the early sedimentary age of the overgrowth's development.

Authigenic tourmaline is not a mineralogical curiosity and is found much more frequently than generally thought. Within the central part of the Appalachian geosyncline there are at least three major horizons of the development of authigenic tourmaline: the Upper Cambrian (Gatesburg-Potsdam), first reported by Krynine;[9] the Lower Silurian (Clinton), reported by J. H. C. Martens[10] and confirmed by Krynine; and the Lower Devonian (Oriskany), reported by M. H. Stow[11] and confirmed by Martens[12] and Krynine.[13]

The best known of these horizons is the Oriskany, which shows authigenic tourmaline for a continuous distance of at least 450 miles from southern West Virginia to northwestern New York State and covers a minimum area of 55,000 square miles. In this region Stow has found authigenic tourmaline in 74 out of 116 examined heavy residues and in 30 out of 70 localities.

In the Upper Cambrian (Gatesburg and Potsdam), Krynine has established authigenic tourmaline in places 200 miles apart between State College outcrops (central Pennsylvania), deep wells near Buffalo and outcrops in Dutchess County in New York State.

[9] "Paleozoic Heavy Minerals from Central Pennsylvania and Their Relation to Appalachian Structure," *Proc. Pa. Acad. Sci.*, Vol. XIV (1940), pp. 60–64.

[10] "Petrography and Correlation of Deep Well Sections in West Virginia and Adjacent States," *W. Va. Geol. Surv.*, Vol. IX (1939), pp. 18 and 178.

[11] "Authigenic Tourmaline in the Oriskany Sandstone," *Amer. Min.*, Vol. XVII (1932), pp. 150–52, and "Conditions of Sedimentation and Sources of the Oriskany Sandstone as Indicated by Petrology," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXII (1938), pp. 541–64.

[12] See p. 17 and Pl. XII of ftn. 10.

[13] "Petrology and Genesis of the Third Bradford Sand," *Pa. State College Min. Indust. Exper. Sta. Bull. 29* (1940), p. 35.

FIG. 3.—Authigenic tourmaline within the Paleozoic of the Appalachian region. Figures *3a–3c* show typical morphology of primary (original) occurrences; *3d–3f* show details of the overgrowths; and *3g–3i* show secondary (re-worked) occurrences.

3a) Overgrowth from the Keefer sandstone of Lower Silurian age (horizon II of Table 2). Magnification 250×.

3b) Overgrowth from the Gatesburg-Potsdam sandstones of Upper Cambrian age (horizon I). Magnification 110×.

3c) Overgrowth from the Oriskany sandstone of Lower Devonian age (horizon III). Magnification 70 ×.

3d) "Zone of roots" between overgrowth and core; from the Gatesburg (horizon I). Magnification 127×.

3e) Details of overgrowth, showing inclusions of calcareous mud and bubbles; from the Gatesburg (horizon I). Magnification 120×.

3f) "Zone of roots" between overgrowth and core; from the Oriskany (horizon III). Magnification 150×.

3g) Re-worked and barely abraded overgrowth from the Spitzenberg conglomerate of Triassic age (horizon 11K), originally from the Silurian (horizon II). Magnification 300×.

3h) Re-worked and strongly abraded overgrowths from the Bellefonte sandstone of Middle Ordovician age (horizon 1K), originally from Gatesburg (horizon I). Magnification 180×.

3i) Re-worked and very strongly abraded overgrowth from the Triassic of eastern Pennsylvania (horizon 10K), originally probably from the Silurian (horizon II). Magnification 200×.

In the Clinton (Keefer sandstone), Krynine has collected authigenic tourmaline in localities 300 miles apart.

It is probable that further studies may show the development of authigenic tourmaline over much greater distances within these formations.

A fourth possible horizon (only one locality) of authigenic tourmaline development has been established by Martens[14] in the Upper Silurian (Salina) of West Virginia.

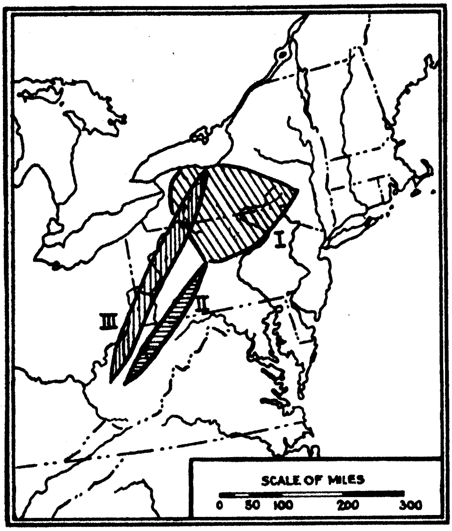

FIG. 4.—Distribution of authigenic tourmaline in the Paleozoic of central Appalachian region. *I*, extent of ***known*** tourmaline authigenesis in the Upper Cambrian (Gatesburg-Potsdam); *II*, same for the Lower Silurian (Clinton-Keefer); and *III*, same for the Lower Devonian (Oriskany).

In addition to these horizons of original, or "primary," development of authigenic tourmaline in the Appalachian region, at least eleven other formations have so far been discovered in which authigenic tourmaline occurs as a reworked, detrital constituent. During the subsidence and concomitant folding of the Appalachian geosyncline, folds developed within the trough, especially on its flanks; and the erosion on these folds of older sediments bearing authigenic tourmaline liberated the tourmaline grains with authigenic overgrowths. During the erosion and transport that follow, the overgrowths may be entirely knocked off the nuclei, leaving only a pitted root zone; or they may survive in a somewhat abraded and worn form. These "secondary" re-worked occurrences are distributed from the Middle Ordovician to the Triassic (Fig. 3 [*3g–3i*]). The economic importance of this fact as a criterion for paleogeographic interpretation in the search for possible oil reservoirs is discussed later in the text.

Each zone of primary authigenic development is characterized by certain morphologic and optical properties: the Cambrian overgrowths are almost colorless and feathery; the Oriskany overgrowths are much more stubby and distinctly bluish; and the Clinton overgrowths are more elongated than the other two. When authigenic tourmaline is developed through a great vertical thickness of strata (for instance, over 750 feet of Potsdam sandstone in the Arcade well near Buffalo), the morphology of the overgrowths may change slightly at different levels, thus providing additional criteria for correlation or differentiation.

Authigenic tourmaline is a veritable guide fossil, both as an original development and as a re-worked occurrence: a piece of Lower Devonian authigenic tourmaline in the Triassic is equivalent to the finding of a Lower Devonian fossil in the Triassic.

The development, both stratigraphic and geographic, of primary and reworked authigenic tourmaline within the

[14] See p. 186 of ftn. 10.

FIG. 5.—This section (crossed Nicols) of Gatesburg orthoquartzite shows development of authigenic tourmaline overgrowth in optical continuity with detrital tourmaline core. Note poor basal parting within the original core. Magnification 250×.

FIG. 6.—Extreme development of perfect authigenic tourmaline overgrowth within the Gatesburg formation. Magnification 100×.

central portion of the Appalachian geosyncline is summarized in Figure 4 and Table 2.

5. *Re-worked tourmaline from older sediments.*—This is probably the most abundant single source of tourmaline found in sediments. After entering a sediment from one of the four primary sources, tourmaline survives the destruction of the sediment during the next cycle of erosion and sedimentation and passes into a younger sediment. Hence, long periods of peneplanation, characterized by vigorous and prolonged chemical decay, are especially favorable for the concentration of tourmaline types in the produced detritus at the expense of other less stable mineral species.[15]

Such periods of diastrophic quiescence increase both the relative abundance of

TABLE 2*

OCCURRENCE OF AUTHIGENIC TOURMALINE IN THE CENTRAL PART OF THE APPALACHIAN GEOSYNCLINE

Period	Primary	Re-worked	Formation and Location
Triassic		11K	Spitzenberg conglomerate, eastern Pennsylvania
		10K	Triassic, eastern Pennsylvania
Permian		9K	Exact formation unknown, West Virginia
Pennsylvanian		8K	Cow Run and Buffalo Run sands, West Virginia
		7K	Pottsville, western Pennsylvania
Mississippian		6K	Pocono, central Pennsylvania
Devonian		5K	Venango sand, western Pennsylvania
		4K	Bradford sand, northwest Pennsylvania
	III-S, M, K		Lower Devonian centering around Oriskany but including Huntersville, Shriver, Helderberg, etc. From northwest New York through central Pennsylvania to southwest West Virginia
Silurian	II*a*-M		Salina, Kanawha County, West Virginia
	II-M, K		Clinton (Keefer sandstone of central Pennsylvania and West Virginia)
		3KM	Tuscarora of central and eastern Pennsylvania. White Medina of West Virginia, Albion sandstone
Ordovician		2K	Juniata of central Pennsylvania
		1K	Bellefonte sandstone of central Pennsylvania
Cambrian	I-K		Upper Cambrian of central Pennsylvania (Gatesburg formation) and New York State (Potsdam sandstone)

* K, reported by Krynine and associates; M, reported by Martens; S, reportedby Stow; "Primary" means original development and "Re-worked" means detrital secondary occurrence.

[15] P. D. Krynine, "Provenance vs. Mineral Stability as a Controlling Factor in the Composition of Sediments" (abstract), *Bull. Geol. Soc. Amer.*, Vol. LIII (1942), pp. 1850–51.

tourmaline in the following sediment and also the *absolute number* of tourmaline varieties in it. Up to twenty-one tourmaline varieties have been found in some sediments.

This is a very schematic outline of the origin of tourmaline types, and the subject deserves considerably more study.

DISTRIBUTION OF TOURMALINE IN SEDIMENTS

Tourmaline is found in practically all detrital sediments, and there are very few heavy concentrates which do not contain some of it. Also, there is probably even more tourmaline in sediments than is generally thought, because many tourmaline varieties are easily mistaken for other mineral species. For instance, colorless, water-clear (nonpleochroic) tourmaline can be—and frequently has been—mistaken for various other, much more fancy, minerals, among which andalusite and, to some extent, topaz have probably been foremost. Nonpleochroic green and brown varieties have been confused with hornblende and biotite.

The bulk of the tourmaline and the greatest diversification of tourmaline types occur within re-worked, second-cycle rocks, made up of quartz and detrital chert, such as graywackes and orthoquartzites. These are the sediments formed during periods of low or moderate deformation of the earth's crust. The relation between the mineral composition of a sediment and the intensity of diastrophism during the period of its formation has been discussed elsewhere (Krynine[16]) and is summarized in Figure 11, after having been shown in some detail in Figures 7–10. This distribution of tourmaline closely parallels that of zircon, another ultra-stable mineral. The tourmaline-zircon suite (reinforced by some rutile) occurs in *all* sediments but predominates over almost all other nonopaque heavy minerals, possibly in as much as 60–65 per cent of the medium-grained detrital rocks and monopolizes the nonopaque assemblage, almost to the complete exclusion of all other constituents, in no less than 30–35 per cent of the same detrital rocks.

Although tourmaline and zircon tend to get into the same rock, they do not, as a rule, accumulate equally in a given part of the rock. This is due to their notable difference in specific gravity (tourmaline about 3.1, zircon about 4.5) which results in local placer-like concentrations of one or the other in response to local variations in current velocity. As a whole, zircon tends to gravitate into a finer grade-size than tourmaline (because of zircon's greater density). In addition, within the same grade-size of the same formation the ratio between tourmaline and zircon may fluctuate from 90:10 through 50:50 into 10:90 within a geographical distance of 1 mile or less or within a stratigraphic interval of a couple of feet. This fact explains some of the early failures in trying to use the zircon-tourmaline ratio for correlation purposes.

STUDY AND INTERPRETATION OF TOURMALINE VARIETIES IN SEDIMENTS

As in all heavy-mineral work, the study of tourmaline can yield the following results: (1) establish the petrology of the source area, both ultimate and immediate; (2) establish the general diastrophic, tectonic, and climatic history of both source area and basin of

[16] *Diastrophism and the Evolution of Sedimentary Rocks* (syllabus outline of lecture) (Tulsa: Distinguished Lecture Committee of Amer. Assoc. Pet. Geol., 1943).

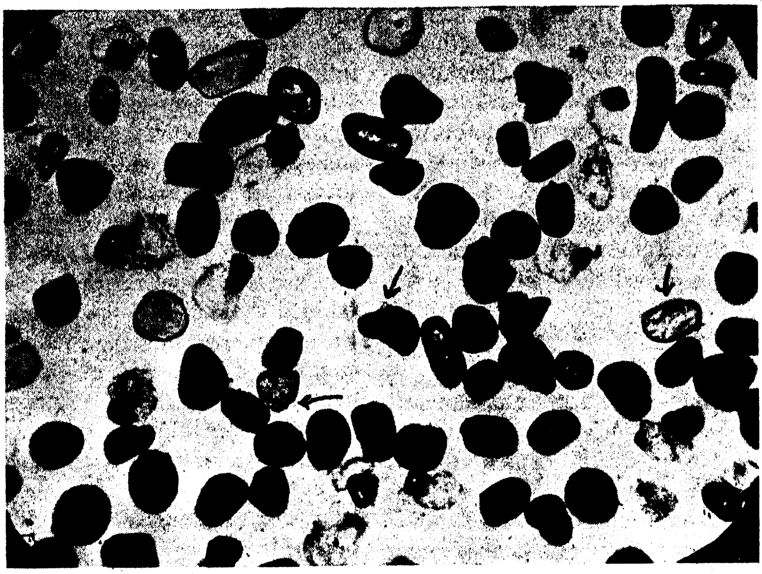

FIG. 7.—Typical heavy residue from a primary first-cycle orthoquartzite, the Gatesburg formation of the Upper Cambrian age from central Pennsylvania. This so-called "Cambrian assemblage" (see Fig. 14) consists of *rounded* tourmaline (and some zircon) grains. There are thirteen tourmaline varieties, which are analyzed in Fig. 12. Some grains show weak development of authigenic overgrowths (arrow). Magnification 55×.

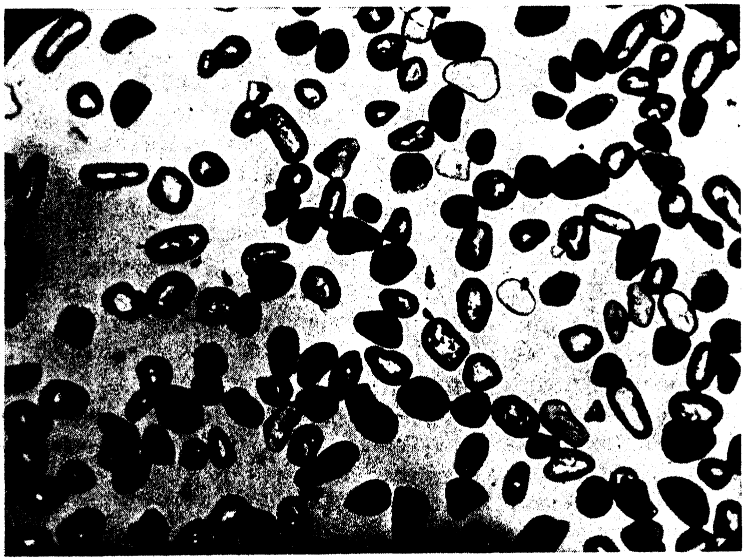

FIG. 8.—Typical heavy residue from a second-cycle orthoquartzite, the Bellefonte sandstone of Middle Ordovician age from central Pennsylvania, produced through erosion and re-working of the Gatesburg formation. Tourmaline shows same rounding and identical frequencies of the same thirteen varieties as in Fig. 7, which are always constant, regardless of local fluctuations in the tourmaline-zircon ratio. Authigenic overgrowths are abraded and barely visible, as shown in Fig. 3 (*3h*). Genetic relationships between Gatesburg and Bellefonte are shown in Fig. 13. Magnification 52×.

sedimentation; (3) establish paleogeographic relations between ancient land and sea before and during deposition of the sediment; (4) establish correlation and differentiation criteria for the formation under study; and (5) as a result of 1, 2, 3, and 4, important economic results can be attained.

In order to proceed with such studies, it is necessary to establish the ultimate and immediate provenance of the tourmaline and the history of the grains subsequent to the uncovering of the source area. The amount of detailed work necessary to do this will depend upon which one of the following three types of provenance is met:

a) There is only one, or at most two, closely related tourmaline varieties, both of which came from the same parent-rock and hence have similar color and morphology and are in the same stage of modification.

b) There are several varieties of tourmaline which came from entirely different parent-rocks and hence differ considerably in color and internal morphology, but all of them have been eroded at the same time within the same source area and hence have suffered approximately the same amount of modification and thus show the same amount of rounding. Such assemblages from the same source area can be treated as a unit.

c) There are several varieties of tourmaline which came from different source areas and were eroded at different times and under different tectonic conditions; hence the varieties differ in color, internal morphology, and rounding.

Examples of (*a*) are found in many continental formations like the Triassic alluvial fans of the Connecticut Valley (as shown in Fig. 10) or some of the deltaic branches of the Silurian Bloomsburg red beds in central Pennsylvania.

The best example of (*b*), i.e., a mixed but uniformly modified source, is found in the Cambrian sediments (specifically the Upper Cambrian Gatesburg and Potsdam formations and their equivalents) of Pennsylvania and New York State, which contain thirteen tourmaline varieties, all perfectly rounded and always recurring in exactly the same relative proportions (Fig. 12). This Cambrian assemblage, which is shown in Figure 7, is easily recognized when it is found in higher Paleozoic strata produced by the re-working of the Cambrian beds (Fig 8).

Examples of (*c*) are found throughout the world within the middle and upper members of geosynclinal sediments. Fine examples come from the Upper Ordovician, Silurian, Devonian, and Mississippian graywackes of the Appalachian region. In these cases, in addition to the Cambrian assemblage, other, much less well-rounded, tourmaline types appear. Such a mixture from the Bradford sand is shown in Figure 9.

The recognition of possibilities (*a*) to (*c*) and its practical application to the solution of problems 1–4 rests upon a thorough breakdown of the tourmaline varieties present into usable types. This differentiation should proceed on the basis of the external shape and internal morphology of the tourmaline grains.

Krynine[17] and O. F. Tuttle[18] have divided Paleozoic Appalachian tourmalines into two rounding classes: very well rounded versus angular and idiomorphic. Within the rounded class, thirteen varieties have been established, based on six

[17] "Paleozoic Heavy Minerals from Central Pennsylvania and Their Relations to Appalachian Structure," *op. cit.*, pp. 61 and 62.

[18] "Heavy Minerals of the Ordovician-Silurian Boundary in Central Pennsylvania," *Proc. Pa. Acad. Sci.*, Vol. XIV (1940), pp. 55–59.

FIG. 9.—Typical heavy residue from graywacke showing, among very few other mineral species, tourmaline grains (arrows) of many varieties and of mixed habits: idiomorphic, hypidiomorphic, fractured, rounded, and refractured. From the Bradford Third Sand (Devonian of Pennsylvania). Magnification 80×.

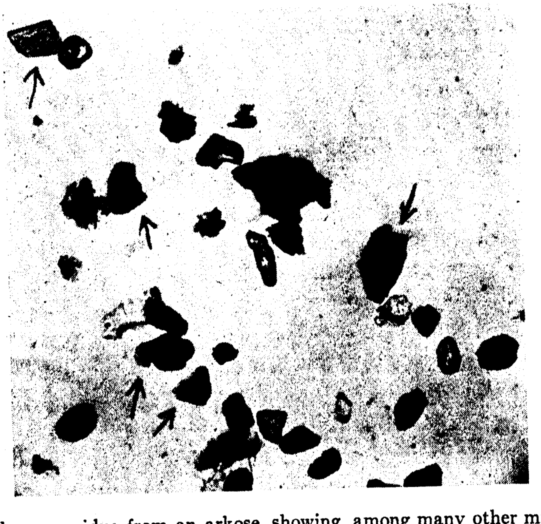

FIG. 10.—Typical heavy residue from an arkose, showing, among many other mineral species, such as epidote and monazite, also tourmaline grains (arrows) of only one variety (green) and of idiomorphic and hypidiomorphic (fractured) habit. From the Triassic of Connecticut. Magnification 50×.

main color classes, three additional shades, and seven types of inclusions. The idiomorphic and angular class has been less exhaustively studied but has yielded, so far, six color classes and four inclusion types, making a total of eight types. In the Bradford sand all twenty-one types are present.[19] A somewhat similar system has been used by Krynine and G. A. Thompson[20] in the Uinta, Weber, and Green River formations of Utah.

Gordon Rittenhouse,[21] for the Mississippian of Ohio and West Virginia, divides tourmaline into three types of rounding (round, subangular, and angular) and, when necessary, uses about five or six colors for further differentiation.

J. C. Griffiths,[22] for the Tertiary oil sands of Trinidad, uses a very comprehensive scheme of five main colors and seventeen final color shades, modified by nine stages of rounding, from idiomorphic to completely rounded, thus allowing for 153 possibilities.

EXAMPLES AND PRACTICAL APPLICATIONS

1. *Origin of the Bellefonte sandstone and Cambro-Ordovician paleogeography of west-central Pennsylvania.*—A monotonous succession of over 5,000 feet of Lower and Middle Ordovician limestones and dolomites in Centre County, Pennsylvania, is interrupted by a 15-foot sandstone layer. This formation, the Bellefonte sandstone, was investigated by the writer and Tuttle in 1938.[23] It shows pronounced lateral changes, passing abruptly from a quartzite into a sandy clastic dolomite and then changing back into a quartzite again. Petrographically it is a mixture of two end-members—a pure rounded quartzitic sand and a subangular gravel made up of dolomitic pebbles. The heavy minerals consist almost exclusively of tourmaline and zircon mixed in all proportions.

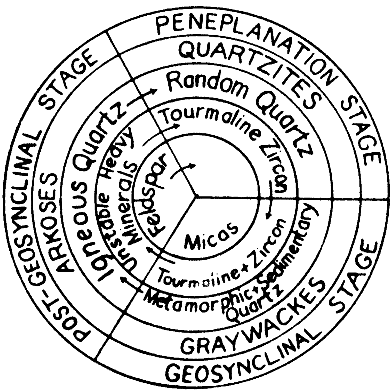

FIG. 11.—The three main diastrophic stages, showing the predominant petrographic types and mineralogical suites common to each stage and illustrating the paragenetic relationships of the tourmaline assemblages, illustrated in Figs. 7, 8, 9, and 10.

This sandstone proved to be made of re-worked detritus produced by the erosion of the Upper Cambrian Gatesburg formation, which normally is stratigraphically located more than 3,500 feet below the Bellefonte sandstone. This conclusion was based on the following evidence:

a) Both formations contain almost identical percentages of the same tangible thirteen varieties of rounded tourmaline. This is shown in Figure 12. The possibilities of both formations being de-

[19] See pp. 30 and 34–36 of ftn. 13.

[20] "Petrologic Study of Some Rocks of the Uinta Basin and Uinta Mountains, Utah" (unpublished B.S. thesis, The Pennsylvania State College, 1941).

[21] "Investigation of Oil and Gas Sands in the Appalachian Basin," *Producers Monthly*, Vol. VIII, No. 10 (1944), pp. 19–21.

[22] (Trinidad Leaseholds, Ltd.), personal communication of October 26, 1943.

[23] See ftn. 8.

rived from a hypothetical common source are untenable on petrologic and statistical grounds.

b) The rounded tourmalines in the Gatesburg formation have developed,

c) Certain rock fragments within the Bellefonte (such as some types of siliceous oölites) can be traced to the Gatesburg formation and also to some Lower Ordovician rocks.

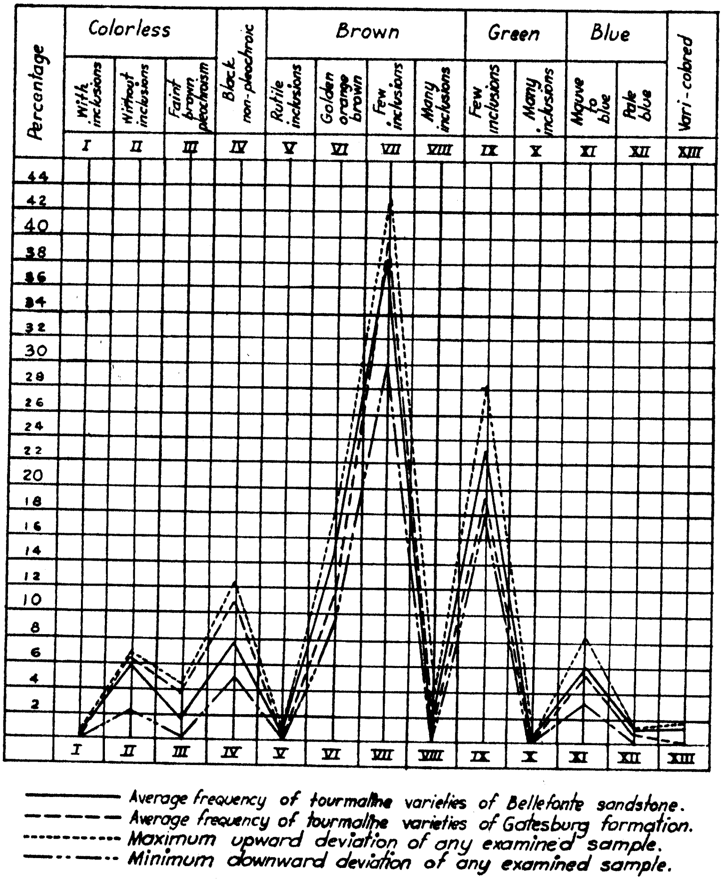

FIG. 12.—Correlation of two Paleozoic formations in Pennsylvania and New York State by means of frequency of tourmaline types.

after their deposition, striking authigenic overgrowths of colorless sedimentary tourmaline (as discussed before), which are shown in Figures 3 (3*b*), 5, 6, and 7. The rounded tourmalines in the Bellefonte sand also have overgrowths, but these are abraded and worn (Fig. 3 [3*i*]).

This interpretation indicates a 3,500-foot hiatus between the Gatesburg and the Bellefonte. This break implies emergence, truncation, and erosion of the Gatesburg formation somewhere not very far from State College. The relative nearness (possibly less than 75 miles) of the area of emergence and truncation of

the Gatesburg is based upon the textural and physical characteristics (coarseness and extreme angularity) of some of the rock fragments within the Bellefonte sandstone which point toward a rather short transport.

The Gatesburg formation in its original unweathered condition is a mixture of sandy dolomites and calcareous orthoquartzites, with the sandy portions forming 20–30 per cent of the whole. A study of the Gatesburg along the Allegheny front shows that upon subaerial weathering the carbonates are leached out and a loose, highly porous sand is produced. This sandy soil makes up the "Barrens" north of State College, and at many places the sand forms highly porous and permeable zones exceeding 30 feet in thickness. This development is not unlike that which took place in the Oklahoma City oil field. Because of the intense tectonic deformation near the Allegheny front, the thicker sand zones produced by recent weathering on the Gatesburg are somewhat local and patchy in their distribution. However, the truncation and weathering of the Gatesburg formation during Bellefonte time apparently were controlled by a much gentler type of uplift, and hence the surfaces of weathering at that time must have been over much larger uninterrupted areas of sand development, which potentially are good oil reservoirs.

Thus, a study of tourmaline varieties in central Pennsylvania leads not only to a determination of the genesis of a sandstone member of Middle Ordovician age but also to the reconstruction of central and western Pennsylvania paleogeography during the same time. Finally, it points to the very possible existence of a sizable petroleum reservoir of the Oklahoma City type near the Cambro-Ordovician contact in west-central Pennsylvania, possibly less than 75 miles northwest of State College. These petroliferous possibilities, which are schematically shown in Figure 13, deserve consideration and more detailed study.

2. *Origin of the Tuscarora quartzite and the Upper Ordovician tectonic history of the Appalachian geosyncline in east-central Pennsylvania.*—In 1939 O. F. Tuttle[24] under the writer's direction investigated in considerable detail the

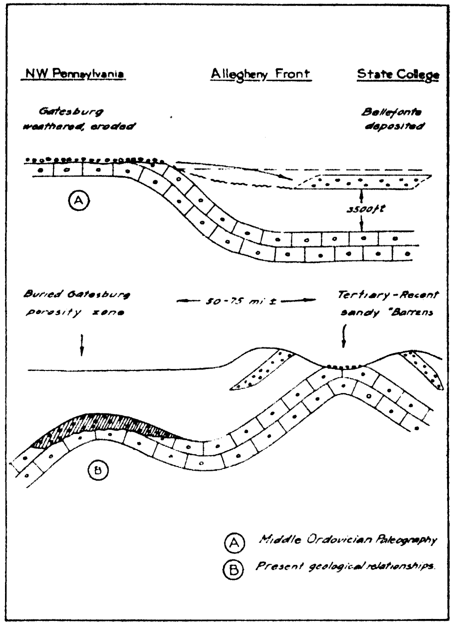

FIG. 13.—Possible development of weathered zone of porosity at the top of the Gatesburg-Potsdam formations in northwestern Pennsylvania. Interpretation is based on a study of the Gatesburg-Bellefonte relationship in central Pennsylvania, as shown, among other criteria, by the relative frequencies of tourmaline types (see Fig. 12).

[24] P. D. Krynine and O. F. Tuttle, "Petrology of Ordovician-Silurian Boundary in Central Pennsylvania" (abstract), *Bull. Geol. Soc. Amer.*, Vol. LII (1941), pp. 1917–18; see also O. F. Tuttle, "Petrographic Interpretation of the Ordovician-Silurian Boundary Problem in Central Pennsylvania" (unpublished M.S. thesis, The Pennsylvania State College, 1940).

petrography of the Ordovician-Silurian boundary in central Pennsylvania. The work included both thin-section and heavy-mineral studies. It was found that the same three main types of heavy-mineral series are characteristic of the entire section but that they occur in different proportions within the different formations investigated. These mineral assemblages, which are named, respectively, the Crystalline Suite, the Cambrian Assemblage, and the Metamorphic Suite, were derived from the erosion of different types of source area. Specifically the Cambrian Assemblage came from the erosion and re-working of Upper Cambrian rocks of the Gatesburg type, as discussed above. The evidence includes the comparison of tourmaline frequencies (along the lines discussed for the Bellefonte), the presence of abraded authigenic overgrowths on tourmaline grains, and finally the presence, within the coarser grained portions of the Tuscarora, of recognizable fragments of Cambrian quartzites.

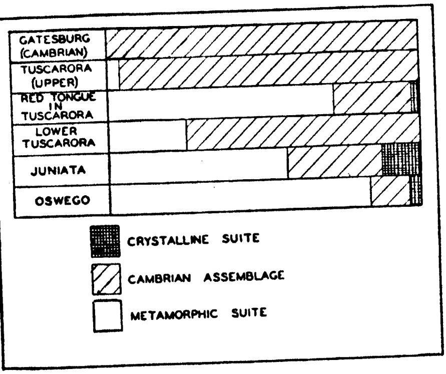

FIG. 14.—Relative distribution of the different mineral assemblages in Cambrian, Ordovician, and Silurian formations of central Pennsylvania. Diagram is graphic adaptation of exact frequency counts on a percentage basis. The "Cambrian assemblage" is made up of rounded tourmalines distributed according to the frequency pattern shown in Fig. 12. This illustration shows origin of Tuscarora through re-working of the Gatesburg. (After O. F. Tuttle.)

The results, showing the relative distribution of this mineral assemblage within the Cambrian, Ordovician, and Silurian formations, are given schematically in Figure 14. The diagram is a graphic adaptation of exact frequency counts on a percentage basis.[25] This section shows that, beginning with the Upper Middle Ordovician, the eastern portions of the Appalachian trough were being elevated and eroded in such a way as to bring to the surface larger and larger areas of Cambrian quartzites, which contributed very largely to the makeup of the Tuscarora formation.

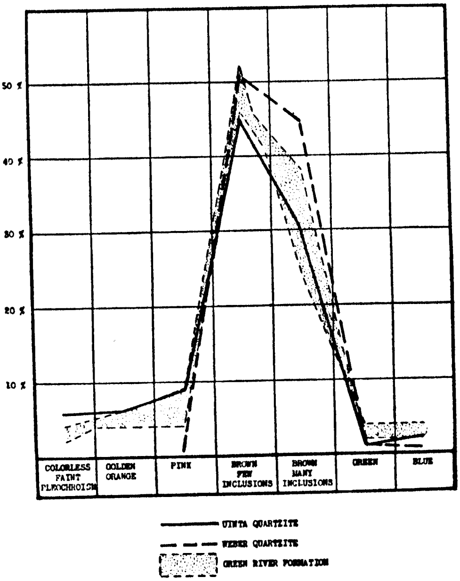

FIG. 15.—Frequency chart of tourmaline types in the Uinta and Weber quartzites and the Green River formation showing that the Weber quartzite is not entirely derived from the Uinta quartzite but that the Green River formation is derived from both the Uinta and Weber quartzites.

[25] Tuttle, "Heavy Minerals of the Ordovician-Silurian Boundary in Central Pennsylvania," *op. cit.*, p. 58.

Thus the study of the petrography of a source area, coupled with a thorough investigation of the mineral composition of a sediment, makes it possible to reconstruct in some detail the tectonic history of a large region. This shows the possibility of applying methods of sedimentary petrography, and especially the study of the tourmaline group, to the solution of problems of structural geology.

3. *Origin of the Green River formation in Utah.*—In 1941 Thompson[26] under the writer's direction investigated the petrography of several formations in Utah. One of the problems was the derivation of the Green River formation. It was desired to know whether the Green River formation was produced specifically through a re-working of the pre-Cambrian Uinta quartzite, or of the Carboniferous Weber quartzite, and whether the Weber quartzite, in its turn, had not also been derived from the Uinta quartzite. The Uinta and Weber tourmalines are rounded; the Green River tourmalines are either rounded, refrac-

[26] See ftn. 20.

TABLE 3*

CORRELATION OF THE SPITZENBERG CONGLOMERATE ON THE BASIS OF TOURMALINE TYPES
(Modified after Allen Heyl)

Tourmaline Types	Martinsburg	Bloomsburg	Triassic	Averaged Spitzenberg	Basal Spitzenberg	Lower Medium Spitzenberg	Middle Spitzenberg	Upper Middle Spitzenberg	Top Spitzenberg
Idiomorphic:									
Yellow to brown (K-1)	....	....	×××	××	....	×	....	×	×
Pink to green (K-3)	×	×××	××	××	....	×	×	××	××
Angular:									
Yellow-brown (K-1 modified)	×××	×	×	×××	×	×	×	×	×
Green (K-2)	×××	....	×	×	....	....	×	....	××
Blue (K-4)	....	....	×	××	....	....	×	×	....
Rounded:									
Black (K-IV)	×	....	××	×	....	....	×	....	....
Golden orange (K-VI)	×	....	××	×	....	....	×	....	....
Dark brown (K-VII and VIII)	×	....	××	×	....	×	×	....	....
Green (K-IX and X)	....	....	××	×	....	....	×	....	×

* K, Krynine's basic tourmaline types as established in the Bradford sand; ×××, abundant; ××, common; and ×, present.

tured (meaning rounded and subsequently broken up), or angular. Figure 15 shows the distribution of the frequencies of *rounded* tourmalines within the three formations. It shows that the

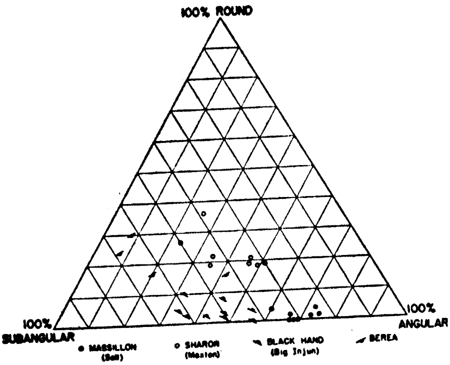

FIG. 16.—Roundness diagram for tourmaline ($\frac{1}{8}$–$\frac{1}{16}$-mm. size), as used by Rittenhouse for differentiation between Massillon, Sharon, Black Hand, and Berea sandstones in Ohio, Pennsylvania, and West Virginia.

Green River formation is a mixture derived from both the Uinta and Weber quartzites and that the Weber quartzite was not derived exclusively from the Uinta quartzite.

4. *Correlation of the Spitzenberg conglomerate of eastern Pennsylvania.*—Mount Spitzenberg, near Hamburg, Pennsylvania, is capped by a conglomerate of uncertain age. It has been variously considered as an Ordovician or Silurian formation or possibly as a Triassic outlier separated from the main eastern Pennsylvania Triassic area. The problem was investigated petrographically by Allen Heyl[27] under the writer's direction in 1940. In addition to pebble counts and thin-section work, studies were made of the tourmaline varieties present in the Spitzenberg, the Triassic, and the Ordovician-Silurian (Martinsburg-Bloomsburg). The results of the tourmaline work are summarized in Table 3. This work was done on the basis of a qualitative or semi-quantitative estimation of relative abundances rather than on the basis of exact frequency counts. It shows, nevertheless, the close relation between the Spitzenberg and the Triassic and served as one of the several methods of petrographic evidence used to correlate the Spitzenberg and the Triassic.

5. *Differentiation of Upper Paleozoic oil and gas sands in the Appalachian Basin.*—Preliminary investigations by Rittenhouse[28] show the possibility of successful differentiation between several extremely similar and closely related Mississippian oil sands of eastern Ohio (Sharon, Berea, Blackhand, and Massillon sands). The first step of Rittenhouse' procedure is a differentiation on the basis of the relative amount of rounded tourmalines within the four sands, as shown on Figure 16. This is followed by a series of additional tests according to

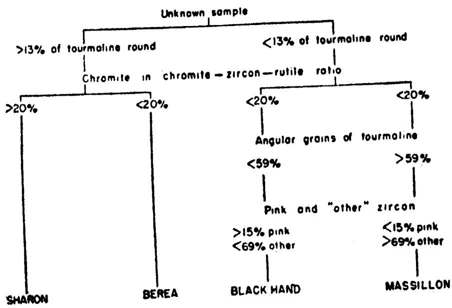

FIG. 17.—Flow sheet showing combined use of tourmaline roundness and other criteria for differentiation between several Paleozoic formations of the Appalachian region. (After Gordon Rittenhouse.)

the pattern of the flow sheet shown in Figure 17, which also involves the relative frequency of angular tourmaline grains.

[27] "A Study of the Spitzenberg Conglomerate, Berks County, Pa." (unpublished B.S. thesis, The Pennsylvania State College, 1941).

[28] See ftn. 21

SUMMARY AND CONCLUSIONS

The tourmaline group is one of the most abundant and most significant members of the heavy-mineral residues of sediments. Its study will repay itself many fold. Tourmaline can be used both for correlation and differentiation of formations and for successful interpretation of ancient paleogeographic conditions, thus becoming, in some cases, a direct oil-finding tool.

ACKNOWLEDGMENTS.—Many of the concepts and facts discussed in this paper were evolved during the teaching of a course in sedimentology at The Pennsylvania State College from 1937 on. During this work the writer was assisted, in one way or another, by the following former students in geology of The Pennsylvania State College: Richard Gault, Frank Goettman, E. T. Heck, Allen Heyl, Randall Jacobs, Jr., Jack Kellberg, M. R. Klepper, Fred Swain, George Thompson, O. F. Tuttle, and Frank Whitmore, Jr. The help of Messrs. Tuttle and Klepper was particularly noteworthy.

Rock specimens which later on proved to contain authigenic tourmaline were given to the writer by the following persons: most of the New York State material by Mrs. E. B. Knopf and Messrs. F. M. Swartz and Parke A. Dickey; and some portions of the West Virginia material by Messrs. C. A. Bonine, E. T. Heck, and J. H. C. Martens. The origin and significance of authigenic tourmaline were discussed many times with the late Professor A. P. Honess. The suggestions of Dr. Honess helped very much in clarifying this phase of the work. Mr. Howard Lucas helped considerably with the photographic work and Mrs. Martha H. Back with the preparation of the manuscript.

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NATURAL GLASS FROM MACEDON, VICTORIA, AND ITS RELATIONSHIPS TO OTHER NATURAL GLASSES

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ABSTRACT

A small quantity of natural glass from Macedon, Victoria, is shown to be like Darwin glass from Tasmania. The glasses from both localities are compared and contrasted with natural glass from other parts of the world.

The results of secondary fusion of rocks under special circumstances during the fierce burning of tree trunks at two localities in Victoria suggest that these glasses may have developed during forest fires. This casts further doubt on the belief that Darwin glass is of tektitic (extraterrestrial) origin.

INTRODUCTION

Two small pieces of natural vesicular glass, donated to the Melbourne University Geological Museum in June, 1931, by Mr. F. H. McK. Grant, were collected during 1920 at a locality described as "half a mile above the top reservoir, Macedon, Victoria." Mr. Grant, Jr., reported that he found them resting on the surface of ground bare of vegetation.

The glass resembles Darwin glass described by F. E. Suess;[1] Loftus Hills;[2] T. W. E. David, H. S. Summers, and G. A. Ampt;[3] and H. Conder[4] from the Jukes-Darwin mining field in west-central Tasmania.

Further searches for pieces of the glass at Macedon have proved unsuccessful. Since only two fragments have been discovered, it is possible that they were transported there by human agencies. But if not brought in by man, the glass is of especial interest in being the only material found outside Tasmania closely comparable with Darwin glass.

DESCRIPTION OF THE GLASS

One piece of Macedon glass, weighing 2.735 gm., is dark gray in color; the other (2.215 gm.), light greenish-gray. Fracture surfaces have a highly vitreous luster, weathered surfaces are dull to subvitreous. Thin edges of the glass are translucent. The hardness is just under that of quartz. The specific-gravity values are 2.080 for the dark-gray glass, and 1.935 for the light greenish-gray glass.

The specific-gravity values are comparable with those for Darwin glass, given by David, Summers, and Ampt[5] as ranging from 1.874 to 2.180 (vesicular glass) and as 2.296 (material in the powdered state). Refractive indices are also similar, the darker Macedon variety being 1.485–1.490, as determined by the immersion method, Darwin glass being 1.486 and 1.497.

The two irregularly shaped pieces of Macedon glass both have numerous subcircular bubble pits and cavities (Fig. 1), ranging from a fraction of a millimeter up to 6 mm. $\times$ 10 mm. in size. The walls of the larger cavities have the appearance of "hot polish," but higher magnifica-

[1] "Rückschau und Neueres über die Tektitfrage," *Mitt. d. geol. Gesellsch. Wien*, Vol. VII (1914), pp. 51–121.

[2] "Darwin Glass," *Rec. Geol. Survey Tasmania*, No. 3 (1915), pp. 1–16.

[3] "The Tasmanian Tektite—Darwin Glass," *Proc. Roy. Soc. Victoria*, Vol. XXXIX, Part II (new ser., 1927), pp. 167–90.

[4] "Darwin Glass," *Ind. Australian and Min. Stand.*, Vol. LXXXIX (1934), pp. 329–30.

[5] Ftn. 3.

tions reveal minute pits and fine flow lines. The highly vesicular character of the glass might indicate boiling of the more volatile silicates in the original material. Temperatures of at least 2,500° C. would be necessary to bring about such action. On the other hand, the vesicles could be due to reactions liberating gases, such as CO_2, SO_2, combined water, absorbed air, or the various gases evolved during the thermal decomposition of minerals, such as hornblende, when heated to 1,000° C.

A white to pink-colored, powdery substance, made up of small subangular quartz grains in a fine-grained cryptocrystalline base (Fig. 2), occurs in some bubble pits. It is sometimes almost completely enclosed by thin films of glass, is firmly attached to the cavity walls, but does not occur in the cavities within the interior of the glass (Fig. 2). It is uncertain whether this material is residual source substance or secondary in origin.

Thin sections of various natural and artificial glasses were prepared for comparison with Macedon glass. Samples of Wabar glass from Arabia were not available for this purpose, but its structures have been illustrated by L. J. Spencer.[6] Figure 3*C* is a sketch from one of Spencer's illustrations. Henbury glass was also figured by Spencer.[7] The following are descriptions of thin plates cut from the various glasses.

Macedon glass.—Colorless, with few smoke-colored streaks and numerous

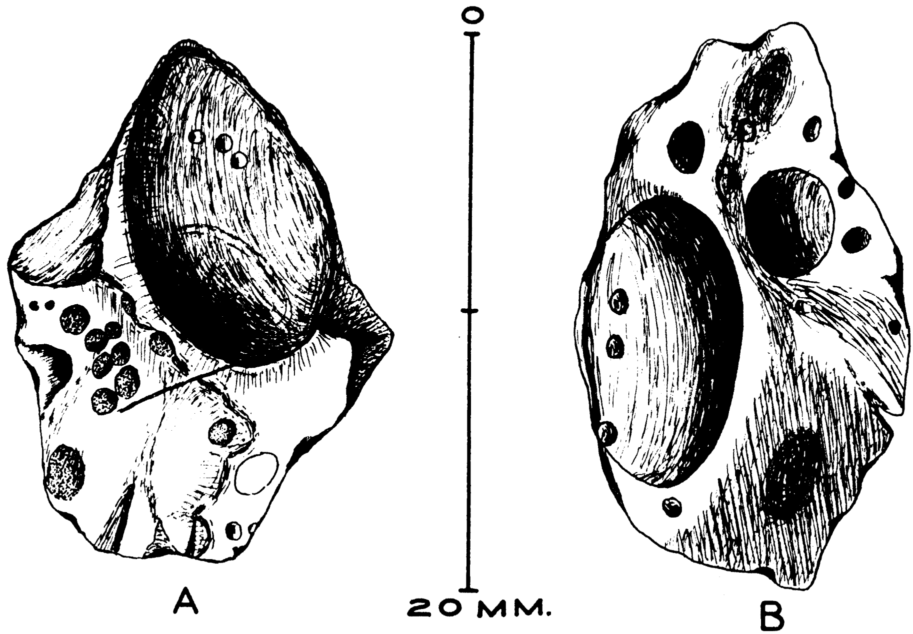

FIG. 1.—Sketch of the outer surfaces of natural glass from Macedon. *A*, light-colored piece; *B*, dark-colored piece. Both pieces show large cavities and smaller bubble pits.

[6] "Meteoric Iron and Silica Glass from the Meteorite Craters of Henbury (Central Australia, and Wabar (Arabia)," *Min. Mag.*, Vol. XXIII (1933), Pl. XIX, Figs. 23 and 24, pp. 387–404.

[7] *Ibid.*, Pl. XX, Fig. 25.

bubble cavities (Fig. 3*B*). Mainly isotropic, with birefringent material in a few cavities at the edges of the sample. The flow lines are conspicuous. The only inclusions within the glass are occasional irregular, elongated, and twisted particles with a pinkish cast, regarded as lechatelierite[8] that has not been entirely absorbed into the homogeneous portions of the glass. In all of these characteristics, Macedon glass is similar to Darwin glass.

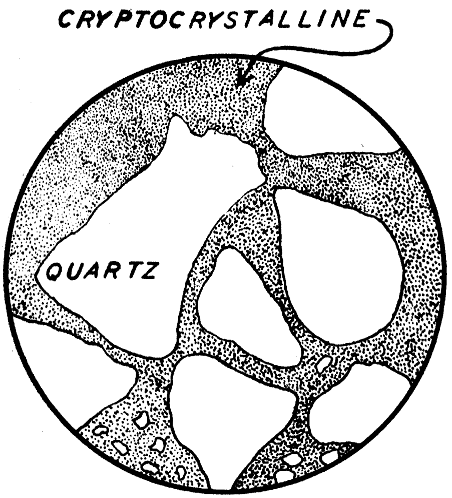

FIG. 2.—Sketch microsection showing subangular quartz grains set in microcrystalline material. ×230. From white substance occurring in some of the bubble pits.

Magnetic metallic spheres, abundant in some specimens of Darwin glass and less prominent in glass from Henbury, Central Australia,[9] are wanting in Macedon glass.

Darwin glass (Fig. 3A).—Resembles Macedon glass in thin section, but flow lines and colored streaks are rather more conspicuous. Paler colored bands in the glass with weak strain polarization are more distinct when a sensitive tint plate is inserted between the crossed nicols. Lechatelierite particles are similar in shape and occurrence to those in Macedon glass.

Henbury glass.[10]—Dark brown to light greenish-brown in color; parts are colorless. Mainly isotropic, with occasional weakly birefringent patches representing nonfused quartz remnants of angular outline and tridymite. The colored portions are sometimes streaky, and rare lechatelierite particles are mostly irregular in shape; some are hooked and twisted.[11] The glass (Fig. 3*D*) is as vesicular as those from Macedon and Darwin.

Artificial glass.—Artificial glass, prepared by the fusion of leached sandy clay collected at Broken Head in the Port Campbell district, Victoria, is similar to Macedon and Darwin glass in many respects. It was formed by fusion in an oxidizing oxyacetylene flame on a carbon boat, from clay containing 6 per cent material soluble in HCl, 27.5 per cent quartz sand, and 66.5 per cent clay constituents. The glass is mainly colorless and isotropic, with numerous pseudomorphs of lechatelierite after quartz (Fig. 4*A*), the presence of which seems to suggest that particles of quartz were fused but not held at fusion temperature long enough to react with and be absorbed by the surrounding material, so that they cooled as SiO_2 in the form of lechatelierite. Many small bubbles occur within the lechatelierite particles and immediately surrounding glass, thus suggesting that they resulted from boiling and emanation of gases during the change from quartz to lechatelierite. The pinkish lechatelierite particles are mostly shaped

[8] George Baker, "Flanges of Australites (Tektites)," *Mem. Nat. Mus. Melbourne;* No. 14, Part I (1944), p. 13.

[9] L. J. Spencer, "Answer to Fenner's 'Origin of Tektites,'" *Nature*, Vol. CXXXII (1933), p. 571.

[10] See Spencer, Pl. XVIII, Fig. 20, of ftn. 6.

[11] Baker, Fig. 3, p. 14, of ftn. 8.

like irregular flints;[12] their color is probably due to differential absorption of light at contacts with the host glass or within the particles themselves, although V. E. Barnes[13] suggested that the pinkish cast is due to reflections from the enclosing glass. In incompletely fused areas, unaltered quartz grains are angular, subangular, and rounded in outline.

Fulgurites.—The lechatelierite glass of fulgurites (Fig. 4*D*) is colorless and isotropic. Numerous minute bubbles are regarded as air vesicles by A. A. Julien.[14] Rare polarizing uniaxial areas confined to exterior parts of the glass are residues of incompletely fused quartz, while biaxial portions represent tridymite. The birefringence of the margins of such areas is weaker than in central portions; this may indicate strain due to differential contraction between the glass and the adjoining quartz. Rare streaks and patches of smoky-gray to brownish-colored ma-

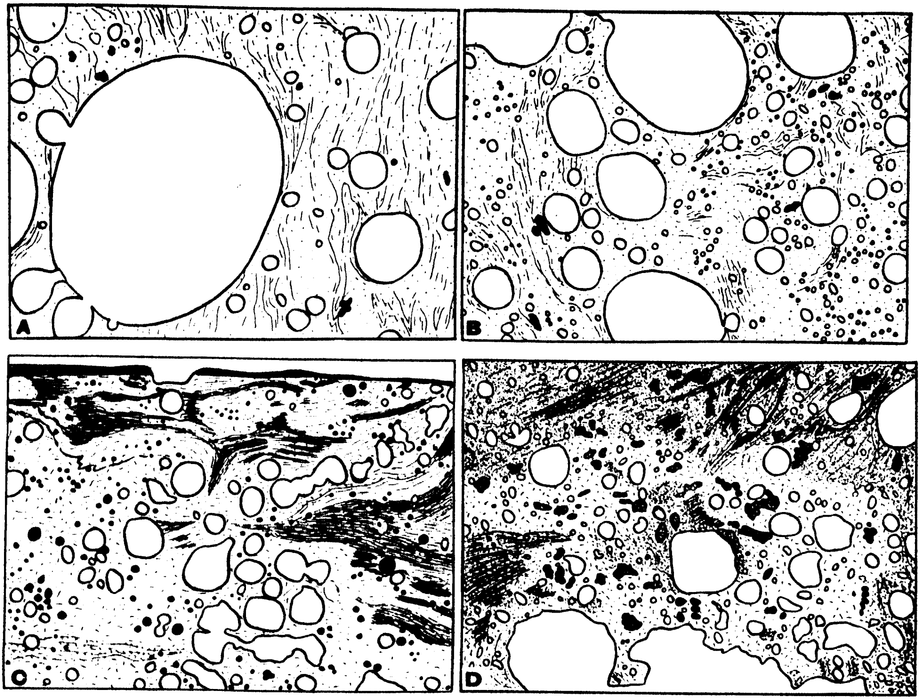

FIG. 3.—Sketch microsections of various natural glasses. *A*, Darwin glass, Tasmania. ×21. Colorless glass with occasional light-brown patches, oval and rounded bubble cavities, flow lines and rare lechatelierite particles (dark stippling). *B*, Macedon glass, Victoria. ×21. Colorless glass with light-brown streaks, numerous small, round gas cavities, flow lines, and rare lechatelierite particles (dark stippling). *C*, Wabar glass, Arabia. ×28.5. Portion of small "bomb" of pale-brown glass with dark-brown (darker shading) and colorless streaks. The black spots are spheres of nickel-iron metal embedded in the glass. *D*, Henbury glass, central Australia. ×21. Dark-brown glass with pale-brown to colorless streaks. Irregular and rounded gas cavities. Lechatelierite particles (dark stippling) relatively common.

[12] *Ibid.*, Fig. 3*H*, p. 14.

[13] "North American Tektites," *Univ. Tex. Pub. 3945* (1940), p. 505.

[14] "A Study of the Structure of Fulgurites," *Jour. Geol.*, Vol. IX, No. 2 (1901), p. 676.

terial, similar to those recorded in a fulgurite from Poland,[15] probably represent glass with rather more iron oxide. Flow lines are inconspicuous, but the arrangement of certain bubbles around larger cavities indicates some glass flowage. Only three lechatelierite particles were seen in one fulgurite section; all are nodular in shape and isotropic, with a lower refractive index than the enclosing glass.

Natural glass from Meteor Crater in Arizona (Fig. 4C).—This consists of colorless lechatelierite glass[16] which is isotropic. In some sections, smoky-brown areas show weak birefringence. The glass is honeycombed with small bubbles. No pinkish-colored particles were observed, although they have been recorded by A. F. Rogers.[17]

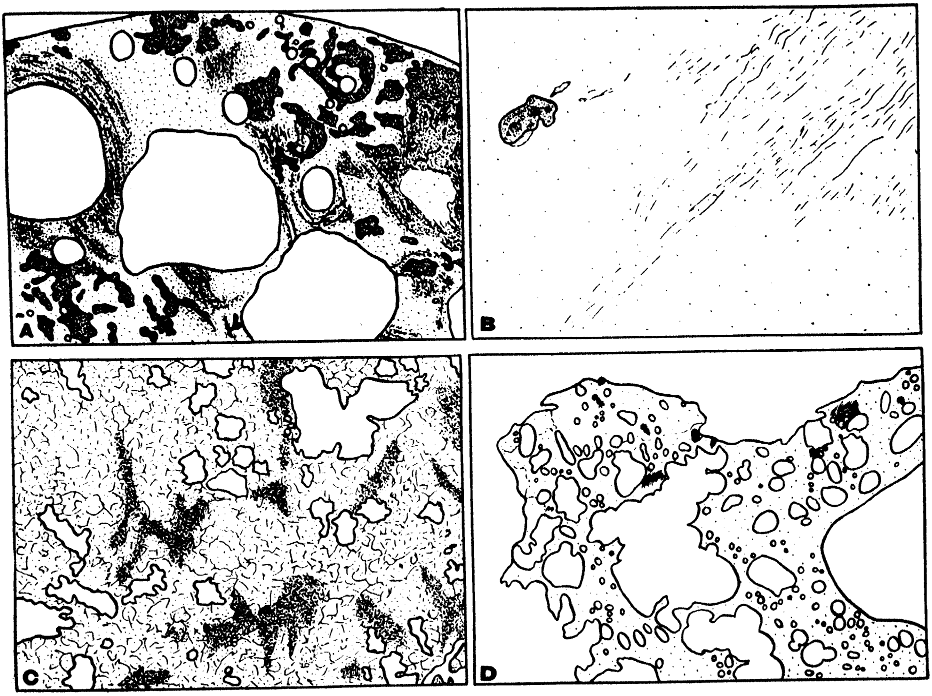

FIG. 4.—Sketch microsections of various natural and artificial glasses. *A*, artificial glass (fused sandy clay). ×68. Light- and dark-brown glass with numerous lechatelierite particles and partially fused quartz grains shown by dark stippling. *B*, silica glass, Sand Sea, Libyan Desert. ×21. Clear, colorless to pale-yellow glass with few fine flow lines and crystal of cristobalite. *C*, silica glass (fused sandstone), Meteor Crater, Coconino County, Arizona. ×21. Irregularly shaped gas cavities and interlocking areas of glass. *D*, silica glass (lechatelierite), fulgurite from Macquarie Harbor, New South Wales. ×21. Showing irregular outer and smooth inner walls. Clear glass with rare flow lines and darker-colored streaks. Dark areas (rare) represent partly fused quartz (probably tridymite or cristobalite).

Libyan Desert glass.—This is clear and

[15] *Ibid.*, p. 673.

[16] A. F. Rogers, "A Unique Occurrence of Lechatelierite or Silica Glass," *Amer. Jour. Sci.*, Vol. XIX (5th ser., 1930), pp. 195–202.

[17] "Natural History of the Silica Minerals," *Amer. Min.*, Vol. XIII (1928), Pl. IV, Fig. 14.

colorless to pale greenish-yellow,[18] with a few brown parallel streaks and bands (Fig. 4*B*). Occasional patches show contorted flow lines; parts are cloudy because of numerous minute bubbles. A few white spherulites of cristobalite were recorded by L. J. Spencer.[19] Thin layers of glass around the cristobalite have a slightly higher refractive index than the rest of the glass. This was caused by rapid chilling and, according to J. W. Greig,[20] results from the cristobalite abstracting SiO_2 from the surrounding glass during chilling. Rare, irregularly shaped bodies of lower refractive index than the host glass are probably lechatelierite particles, although Barnes[21] stated that lechatelierite particles similar to those in tektites are absent from the Libyan glass and remarked that, since this is essentially lechatelierite glass, the absence of the particles is easily explained. It is to be noted, however, that such particles also occur in fulgurites, which are themselves essentially lechatelierite glass.

Artificial silica glass.—This glass, prepared for chemical ware, is clear and colorless in thin section and entirely isotropic. There are no streaks, flow lines, or lechatelierite particles in this well-mixed glass, prepared from selected constituents.

THE VARIOUS GLASSES COMPARED

Considerable variations occur in the complexity of flow-line patterns, number and nature of included particles, bubble content, and color of these glasses.

Macedon and Darwin glass resemble that produced on fusing natural impure clay. The clearer glass from Libya more closely approaches silica glass used for chemical ware, both in purity and in appearance in thin sections. The nature of the glass formed in each instance thus depends primarily upon the character of the original unfused material; secondarily, it depends upon temperature and time involved, irrespective of the means of fusion. Those with fewer lechatelierite particles, a small proportion of the glass showing streaks and bands and few bubbles, indicate more thorough mixing, since most irregularities have been smoothed out in them. The greater vesicularity and slaggy appearance of the natural glasses from Darwin, Macedon, Henbury, and Meteor Crater undoubtedly remove them into a class quite apart from the true tektites.

The refractive indices and specific-gravity values of the various natural glasses examined are compared in Table 1.

The two values for the Meteor Crater glass are quoted from Spencer[22] and from Rogers,[23] respectively. Where available, silica percentages have been included to show the progressive lowering of refractive indices and specific gravities as silica increases; this relationship for many of the natural glasses has been shown in graph form by Spencer.[24]

The position of the Macedon glass in Table 1 suggests a silica value of about 86 per cent, similar to that of Darwin glass. Analyses of the Darwin glass are compared in Table 2 with those of glasses from other parts of the world.

It is seen from Table 2 that Darwin glass (and therefore probably Macedon glass also) is richer in alumina and mag-

[18] L. J. Spencer, "Silica Glass from the Libyan Desert," *Min. Mag.*, Vol. XXIII (1934), pp. 501–8.

[19] "Tektites and Silica Glass," *ibid.*, Vol. XXV (1939), pp. 425–40.

[20] "Immiscibility in Silicate Melts," *Amer. Jour. Sci.*, Vol. XIII (1927), pp. 1-44 and 134–54.

[21] P. 492 of ftn. 13.

[22] See ftn. 19.

[23] Pp. 73–92 of ftn. 17, and ftn. 16.

[24] P. 430 of ftn. 19.

TABLE 1

Refractive Index and Specific Gravity of Natural Glasses

Glass	R.I.	S.G.	Per Cent SiO_2
1. Henbury black	1.545	2.31	68.88
2. Wabar black	1.500	2.24	87.45
3. Darwin pale greenish-gray	1.497	...	87.00
4. Macedon dark gray	1.490	2.08	...
5. Darwin smoky-gray	1.486	2.296	86.34
6. Macedon light greenish-gray	1.485	1.935	...
7. Wabar white	1.468	2.10	92.88
8. Libyan pale yellowish-green	1.462	2.206	97.58
9. Meteor Crater white	1.460	2.10	98.63
10. Meteor Crater white	1.458	2.21	...
11. Artificial (chemical ware)	1.458	2.203	100.00

TABLE 2

Chemical Analyses of Natural Glasses

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV
SiO_2	92.88	87.45	68.88	86.34	87.00	88.764	89.813	98.20	71.70	70.22	70.61	50.87	66.04	57.40	81.03
Al_2O_3	2.64	1.77	5.60	7.82	8.00	6.127	6.207	0.70	13.90	13.96	8.59	14.33	1.55	1.81	2.99
Fe_2O_3	0.23	0.28	8.46	0.63	0.19	...	0.258	0.53	6.70	6.58	2.52	5.37	0.59	0.59	0.58
FeO	0.53	5.77	7.92	2.08	1.93	1.238	0.895	0.24			5.96	7.25	...	...	0.78
MnO	0.01	0.01	0.05	nil.	nil.	tr.	tr.	...	0.02	0.02	0.34	0.58	...	...	tr.
MgO	0.47	0.60	2.03	0.92	0.82	0.575	0.727	0.01	2.70	2.71	0.07	4.51	3.80	5.56	1.15
CaO	1.46	1.90	2.51	0.05	nil.	0.174	...	0.30	5.25	4.65	0.61	8.22	6.00	8.56	8.21
Na_2O	0.42	0.39	0.03	0.15	0.14	0.129	0.010	0.33	n.d.	n.d.	6.77	3.39	6.88	8.98	2.34
K_2O	1.61	0.58	1.43	0.87	0.99	1.363	1.054	0.02	n.d.	n.d.	4.46	1.35	11.98	13.58	2.07
H_2O+	0.32	0.04	0.03	0.43	0.36	...	...	0.03	...	...	...	0.17	...	...	0.20
H_2O-	0.11	0.08	0.05	0.03		...	...	0.03	...	...	...	0.33	...	...	0.04
CO_2	nil.	...	...	nil.	nil.	...	...	...	...	...	...	0.03	...	...	tr.
TiO_2	0.12	0.15	3.64	0.52	0.51	1.240	0.857	0.23	tr.	tr.	0.15	3.38	...	...	0.34
P_2O_5	tr.	tr.	nil.	tr.	nil.	...	...	...	...	...	...	0.07	...	...	0.24
ZrO_2	nil.	...	...	0.11	tr.(?)	...	...	...	...	...	...	...	...	...	...
Cr_2O_3	nil.	...	...	nil.	nil.	...	...	...	...	...	...	...	...	...	...
NiO	nil.	0.35	0.28	nil.	nil.	...	...	0.02	...	...	...	0.06	...	...	...
CoO	nil.	tr.	tr.	nil.	nil.	...	...	...	...	...	...	...	...	...	...
CuO	nil.	nil.	tr.	...	...	...	...	...	...	...	...	...	...	...	...
BaO	nil.	...	...	nil.	nil.	...	...	...	...	...	...	...	...	...	...
SrO	0.01	0.01	nil.	nil.	nil.	...	...	...	...	...	...	...	...	...	...
SO_3	nil.	...	...	nil.	nil.	...	...	...	...	...	...	...	...	...	nil.
Cl	nil.	...	...	nil.(?)	nil.(?)	...	...	...	...	...	...	...	...	...	tr.
S	nil.	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Total	100.81	99.38	100.91	99.95	99.94	99.610	99.821	100.64	100.27	98.14	100.08	99.91	99.53*	99.64†	99.97

NOTES FOR TABLE 2

* Plus 2.69 per cent carbonaceous matter.

† Plus 3.16 per cent carbonaceous matter.

I. White glass, Wabar, Arabia (L. J. Spencer, "Meteoric Iron and Silica Glass from the Meteorite Craters of Henbury [Central Australia] and Wabar [Arabia]," *Min. Mag.*, Vol. XXIII [1933], pp. 387–404; anal. M. H. Hey).
II. Black glass, Wabar, Arabia (*ibid.*; anal. M. H. Hey).
III. Black glass, Henbury, Central Australia (anal. M. H. Hey).
IV. Smoke-gray glass, Darwin, Tasmania (T. W. E. David, H. S. Summers, and G. A. Ampt, "The Tasmanian Tektite–Darwin Glass," *Proc. Roy. Soc. Victoria*, Vol. XXXIX, Part II [new ser., 1927], pp. 167–90; anal. G. A. Ampt).
V. Pale greenish-gray glass, Darwin, Tasmania (*ibid.*; anal. G. A. Ampt).
VI. Olive-green glass, Darwin, Tasmania (L. Hills, "Darwin Glass," *Rec. Geol. Surv. Tasmania*, No. 3 [1915], pp. 1–16; anal. E. Ludwig).
VII. Dirty-white glass, Darwin, Tasmania (*ibid.*; anal. E. Ludwig).
VIII. Greenish-yellow glass, Libyan Desert (L. J. Spencer, "Tektites and Silica Glass," *Min. Mag.*, Vol. XXV [1939], pp. 425–40; anal. M. H. Hey).
IX. Australite glass (flange), Mulka, Lake Eyre District, South Australia (anal. A. B. Edwards).
X. Australite glass (core), Mulka, Lake Eyre District, South Australia (anal. A. B. Edwards).
XI. Obsidian, British East Africa (J. P. Iddings, *Igneous Rocks* [1913], Vol. II, p. 581).
XII. Tachylyte, Meredith, Victoria (anal. A. G. Hall, 1914) *Rec. Geol. Surv. Victoria*, Vol. III, p. 324.
XIII. Straw silica glass, O. B. Flat, South Australia (C. Fenner, "Australites. Part IV. The John Kennett Collection," *Trans. Roy. Soc. So. Aust.*, Vol. LXIV [1940], pp. 305–24; anal. F. L. Dalwood).
XIV. Straw silica glass, Compton Downs, South Australia (*ibid.*; anal. F. L. Dalwood).
XV. Slag formed from charcoal (boxwood) in the suction gas plant, Stawell (anal. F. F. Field, 1924).

nesia but poorer in iron and lime than most of the other glasses, while the Henbury glass is among the most basic.

ORIGIN OF THE NATURAL GLASSES

There seem to be no grounds for suspecting that fulgurites have been formed in any other way than by instantaneous fusion of sands by lightning, as advocated by A. A. Julien,[25] or for doubting that the Henbury, Wabar, and Meteor Crater glasses were formed as products of fusion on meteoritic impact.[26] The latter are found associated with meteorite craters, iron shale, and metallic meteorites. The *Köfelsite* from near Köfels in the Oetz Valley, Tyrol, which was called *meteorschmelz* by F. E. Suess,[27] probably is in the same category. Dr. H. B. Stenzel has suggested[28] that such glasses should be termed "impactites," a very appropriate name for them. The origin of the Libyan, Darwin, and Macedon glasses, however, is debatable because of lack of conclusive evidence.

As Darwin and Macedon glass are so similar in many ways, being to all intents and purposes identical in hand specimens, it is assumed that they were probably formed in a similar manner from similar material. Reviewing theories already presented to account for Darwin glass and including further evidence concerning the formation of natural glass on the earth's surface (neglecting, of course, the chilling of magma and lava), the authors advance the following arguments.

Extraterrestrial origin.—Previously, Darwin glass has been classed with tektites and therefore regarded as having fallen from outer space as pieces of highly siliceous vesicular glass.[29] There is no known means at present of confirming such a theory of origin; but the irregular fragments, some of which are very vesicular, are not in accord with the character of the well-known tektites (regarded by most workers as extraterrestrial).

Several thousand tons of Darwin glass are estimated to have been found[30] scattered over the Jukes-Darwin mining field of western Tasmania, whereas at Macedon, Victoria, some 350 miles away, only two pieces, of total weight 4.95 gm., have been found. There is no record of additional finds in the intervening area, but the possibility exists of burial beneath superficial deposits.

It is doubtful whether the small amount of Macedon glass, situated so far from the main field of occurrence in Tasmania, could have been formed in an extraterrestrial manner comparable to that advocated for Darwin glass.

Artificial origin.—An artificial mode of origin, as advocated by F. Berwerth,[31] has been shown to be unlikely and is unacceptable at the present day.

Origin by lightning fusion.—E. J. Dunn[32] considered that there was more than a cursory resemblance between Darwin glass and the fulgurites from Griqualand in western South Africa. Apart from this suggestion, nothing has been brought forward to support the idea that Darwin glass may have been fused by lightning. In the Macedon district, there is no evidence of the effects of lightning discharge

[25] Pp. 673–93 of ftn. 14.

[26] See ftn. 6.

[27] "Der Meteor Krater von Köfels bei Umhausen im Ötzale, Tirol," *Neues Jahrb., Min. Abt.*, Vol. LXXII (1936), pp. 98–155.

[28] See ftn. 13 (in Barnes' Paper).

[29] David, Summers, and Ampt, pp. 167–90 of ftn. 3.

[30] Pp. 329–30 of ftn. 4.

[31] Können die Tektite als Kunstprodukte gedeutet werden? (Eine Bejahung)," *Centralbl. f. Min.*, 1917, pp. 240–54.

[32] "Additional Notes on Australites. Darwin Glass," *Proc. Roy. Soc. Victoria*, Vol. XXVIII, Part II (new series 1916), p. 227.

on the rocks or soils. Rock fused by lightning has been pictured by Julien,[33] but J. D. Laudermilk and T. G. Kennard[34] found that percussion marks and radial flaking were the common features caused by lightning discharges striking rocks. No such features are evident in the locality from which the Macedon glass was collected. Moreover, it is certain that Macedon glass (likewise Darwin glass) differs from fulgurites in several specific characteristics. Appearance of the surface, as well as difference of form and the absence of birefringent areas from the Macedon glass, makes it apparent that lightning was not the cause of formation.

Origin by fusion of meteoritic impact.—Both Spencer[35] and H. Michel[36] regarded the heat of meteoritic impact as responsible for the formation of Darwin glass. On this hypothesis, siliceous material of terrestrial origin has been fused by the intense heat developed when an iron meteorite strikes the earth's surface. Spencer[37] has pointed out that Suess, a world authority on tektites and silica glass, had originally accepted the Darwin glass fragments as tektites but had later (1933) agreed that Darwin glass should be classed with the silica glass of meteorites. H. Conder[38] also favored an origin by means of meteoritic splash, because of the occurrence in Darwin glass of strings of metallic spheres, which he considered were the same as such strings in Wabar glass from Arabia, a glass undoubtedly arising from the fusion of terrestrial materials by the heat of meteoritic impact. Conder found it difficult to accept previous ideas that the Darwin glass, like tektites, had descended as a kind of meteoritic hailstorm or as a large mass which exploded as it reached the earth.

To account for the fact that some thousands of tons of Darwin glass occur over an area 10 miles long by 6 miles wide, however, the fall of a very large single meteorite or a great number of individual meteorites would have to be postulated. There is no evidence to show that such an event occurred. Neither is there any evidence at Macedon which would indicate that Macedon glass was formed by the fusion of siliceous sands as a consequence of the heat of meteoritic impact, although it is realized that the effects of such impact may be insignificant at times or, if marked, may be rapidly wiped out. Meteorite craters, if formed, may be readily removed by erosion. Metallic meteorites are rapidly oxidized in certain climates, so that all traces of them may be removed by the dispersal of iron oxides in solutions, or they may even be buried from view. Stony meteorites also readily disintegrate in climates like that now extant in the Macedon district. Silica glass may thus be all that remains as evidence of a past meteorite fall—and that only by virtue of its chemical stability. Nevertheless, it is considered highly unlikely that the large amount of Darwin glass and the small quantity of Macedon glass result from meteoritic impact.

Origin by the heat of bush fires.—Origin of natural glasses by this means has to be considered from two aspects. First, the actual fusion of rocks and soils in a forest fire and, second, development of pieces of glass by the accumulation of the silica contained in vegetation.

Certain rock specimens have recently

[33] P. 690, Fig. 3, of ftn. 14.

[34] "Concerning Lightning Spalling," *Amer. Jour. Sci.*, Vol. XXXV (5th ser., 1938), pp. 104–22.

[35] P. 432 of ftn. 19.

[36] "Tektite," *Fortschr. Min., Krist., U. Petrog.*, Vol. XXIII (1939), pp. cxliii–cxlv.

[37] See p. 432, ftn. 19.

[38] See ftn. 4.

been found in Victoria which throw some light upon the way in which secondary fusion of rock fragments can occur at or near the surface of the ground. A specimen of partially weathered anorthoclase trachyte, collected by Mr. Grant, Jr., from the same locality in which the natural glass was found eighteen years previously, shows small partially fused areas on the more weathered surface (Fig. 5). Such areas consist of a thin glassy film, with associated angular anorthoclase crystals. These crystals might be expected to have suffered rounding and embayment on heating; but since they show no evidence of this, it cannot be concluded that fusion has not occurred, because many quartz crystals, for instance, which were only partially fused in the formation of artificial glass from sandy clay, were angular and not embayed. One of the glassy films on this specimen shows structures which resemble the impressions of wood fibers (left-hand fused area in Fig. 5), indicating that a thin portion of the surface of the rock became fused in contact with hot charcoal.

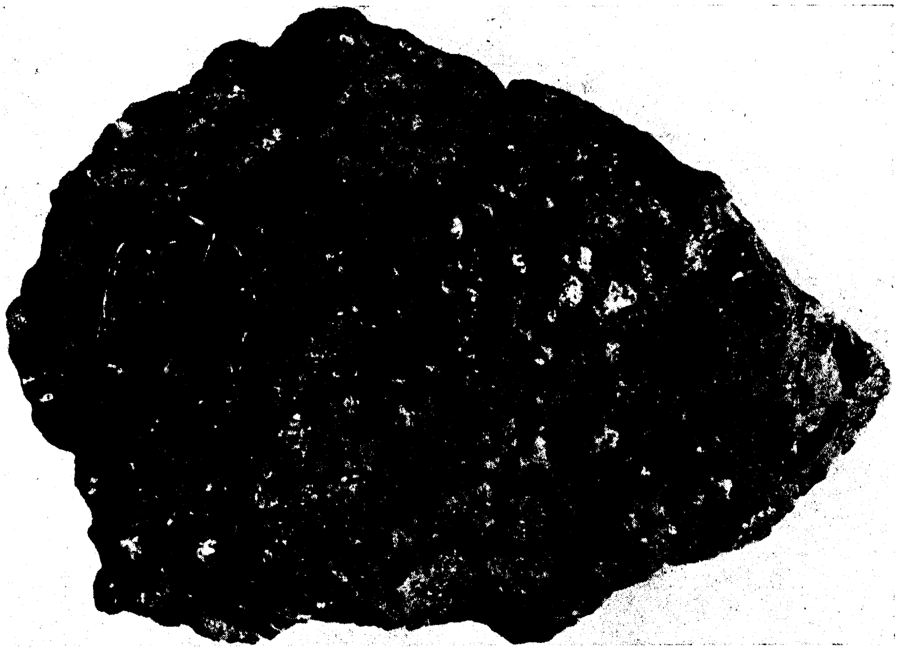

FIG. 5.—Surface of partially fused, weathered anorthoclase trachyte from Macedon, Victoria. ×1.6. Photograph by J. Spencer Mann.

Even more convincing are occurrences of secondarily fused basalt recently discovered by the authors and by Mr. H. R. Samson, on the crater rim of Mount Franklin in central Victoria. Pieces of carbonized wood were found still embedded in the re-fused outer surfaces (Fig. 6) of basalt fragments caught up in a partially burnt-out tree trunk. The tree trunk, of approximately 2 feet in diameter, had fallen over; and scattered around it were films, gobbets, and flat cakes of

glass on basaltic soil (Fig. 7, *B* and *C*). Both the soil from decomposition of the basaltic scoria forming Mount Franklin and fragments of anorthoclase basalt were fused. A crystal of anorthoclase is shown in the top right-hand corner of Figure 6 and, like the anorthoclase crystals from the Macedon trachyte, is quite angular.

Thin sections of the outer re-fused surfaces show a glassy basalt film with a few bubbles and some skeleton crystals of iron oxide; this forms a thin veneer to a vesicular, fine-grained basalt with feldspar, augite, anorthoclase, and olivine crystals. In some examples, the outer re-fused surface basalt has flowed in the manner shown in Figure 7, *A*.

FIG. 6.—Secondarily fused basalt from almost burnt-out tree trunk, Mount Franklin crater rim, central Victoria (natural size). Showing thin glassy surface crust (on *left*) and cellular character of interior. *C* indicates remaining fragments of wood charcoal embedded in cavities. White crystal (*top right*) is anorthoclase, apparently unaffected by the secondary heating. Photograph by Miss M. L. Johnston.

FIG. 7.—Secondarily fused basalt from within and around partially burnt-out tree trunk. *A*, showing rolled-over edge of glassy basalt formed by secondary fusion of vesicular basalt. Natural size. *B*, thin cake of fused basalt soil with impressions of vegetable matter. Natural size. *C*, showing glassy surface of re-fused basaltic scoria; white areas are probably blebs of wood-ash salts embedded in and encrusting the glass. Natural size. Photographs by Miss M. L. Johnston.

The basalt fragments unquestionably suffered secondary fusion when caught up in a burning tree trunk, but there must have been special conditions to bring this about. In most areas examined after bush fires in Victoria, there is no evidence similar to that found at Mount Franklin. It is known that even the extremely hot bush fires in Victoria have little effect on the surface layers of soil in most instances. In the disastrous fires of 1926, bracken ferns from 3 inches deep sent up fronds 13 days after the fires. Clods of earth from the roots of a burnt-out eucalyptus tree at Arthur's Seat, Dromana, Victoria, were only slightly baked and contained beetle cases which had not even been slightly incinerated.

V. E. Barnes[39] has expressed doubt as to whether bush fires are sufficiently hot to form natural glass by fusing products of disintegration on the surface of the earth; but, given the right set of conditions, it seems likely that sufficiently high temperatures can be developed. The only measurements available to the authors of temperatures attained during forest fires indicate that they are usually too low to cause rock fusion. N. C. W. Beadle[40] recorded temperatures of 50° C. in soil at depths of 1 foot from a controlled forest fire allowed to burn for 8 hours. At a depth of 1 inch the temperature was recorded as over 250° C., and at the surface as 450° C. Beadle also stated that the Hawkesbury sandstone soils in New South Wales were not affected to any great extent by fire, the water-retaining capacity, loss on ignition, and pH value not appreciably altering.[41]

If, therefore, forest fires have little appreciable effect upon the physical properties of soils, they should, in the light of Beadle's experiments, be disregarded as a likely agent for the fusion of exposed surfaces of rocks or of disintegration products to form natural glass. Since, however, the ground temperatures recorded by Beadle are practically minimum temperatures, it must be remembered that it is quite easy to get temperatures up to 1,800° C. by drawing air through burning charcoal at a high enough speed. An approach to such high temperatures might be obtained in a bush fire, given the right set of conditions, such as a tall, hollow tree with an unobstructed air path up its middle. These were the circumstances in which the re-fused basalt fragments were produced at Mount Franklin in central Victoria, where, in addition, fluxes from the wood ash assisted in ready re-fusion of the basaltic material caught up in the partially burnt-out tree trunk.

In connection with the second probability—the fusion of the silica content of certain plants and its collection into blebs and gobbets of natural glass during the burning of such vegetable matter—evidence is forthcoming to show that some plants do leave a residue of glass on incineration. Thus R. Spruce[42] stated that *Licania* bark contains a great quantity of silex (=silica), which can be observed in the bark with a hand lens. The burnt bark turns out a flinty mass. It is calcined by the natives of the Amazon and mixed with clay for pottery-making. Then, again, samples of glass resultin from the burning of hayricks and known as "straw silica glass" have been reported from time to time.[43] An example of glass formed from the burning of a tree has

[39] P. 549 of ftn. 13.

[40] "Soil Temperatures during Forest Fires and Their Effect on the Survival of Vegetation," *Jour. Ecol.*, Vol. XXVIII (1940), pp. 180–92.

[41] *Ibid.*, p. 184.

[42] *Notes of a Botanist on the Amazon and Andes*, Vol. I (London: Macmillan & Co., Ltd., 1908), p. 12.

[43] C. Fenner, "Australites. Part IV. The John Kennett Collection," *Trans. Roy. Soc. So. Aust.*, Vol. LXIV (1940), pp. 305–24.

recently been recorded from La Pine in Oregon by J. H. Pruett.[44] Clinkers of fused wood ash were discovered in burnt, hollow tree trunks after forest fires, and these clinkers were referred to as pseudometeoritic glass under the name of "the tree meteorite." The foregoing examples are sufficient to show that natural glass can be formed under certain conditions both by the fusion of rocks during bush fires and by the incineration of silica-bearing plants.

In the light of these observations the question arises as to whether Darwin glass and Macedon glass can have originated in any way during forest fires. In western Tasmania an abundant species of button grass contains up to 2 per cent of silica. This amount might be sufficient to account for the formation, on burning of the plants, of the bleblike and irregular pieces of natural glass like Darwin glass. The lateral and vertical extent of the glass would, under these circumstances, be limited by the distribution of the silica-bearing plants and by the extent of the bush fire.

THE EVIDENCE OF THE MINOR ELEMENTS

Since so little of the glass from Macedon was available, routine chemical analyses were not undertaken; instead, spectrochemical analyses were performed on small chips. Although this type of analysis does not give accurately the amounts of major elements present in the sample (i.e., those of 5 per cent or more), the amounts of minor elements can be assessed fairly closely. Hence spectrochemical analyses of various natural glasses of known origin were made conjointly with those of Macedon glass in the hope that if any correlation could be established between the minor-element content of a glass and its mode of origin, some light would be thrown on the origin of Macedon glass.

The comparison table (Table 3) thus contains the results of spectrographic analyses of the following glass types: (1) glass produced by fusion of sedimentary material during meteoritic impact (Meteor Crater and Henbury glass); (2) glass produced by fusion of sediments during lightning discharge (fulgurite glass); (3) tektite glass (from core and flange of Mulka australite); and (4) volcanic glass (Pelée's hair, obsidian, and tachylyte).

Analyses were also performed on glass produced by fusion of sedimentary material in an oxyacetylene flame and on two naturally occurring glasses (Libyan and Darwin) of uncertain mode of origin. The latter resembles Macedon glass and, like it, was divided into a light and a dark variety for analysis.

TECHNIQUE OF ANALYSIS

The analyses were carried out with the aid of a Hilger Medium quartz spectrograph, the range 2,100–4,000 A.U. occupying about 7 inches of a 10-inch photographic plate. The excitation source was a low-voltage D.C. arc, the method of cathodic excitation described by L. W. Strock[45] being used. High-purity graphite electrodes were used, the lower (negative) electrode being turned and drilled to form a thin-walled cup for the reception of the glass samples. Cutting and drilling were performed in a single operation by a revolving cutter mounted coaxially about the drill. The hard steel of the cutting system did not give rise to any detectable contamination of the electrodes.

Small samples for arcking were obtained by breaking off fragments of the

[44] "The 'Tree Meteorite' of La Pine, Oregon," *Pop. Astr.*, Vol. XLVII (1939), pp. 150–51.

[45] *Spectrum Analysis with the Carbon Arc Cathode Layer* (London: Adam Hilger, 1936).

glass specimens with a hardened steel point. The fragments were bonded together in the cup of the negative electrode with cellulose acetate solution, which, when dry, protected the samples from contamination from dust and also tended to prevent them from being ejected from the cup as the arc was being struck. The arc was struck at 200 volts, a series resistance being used to limit the current to 3 amperes for the first 10 seconds of the burning period, after which the current was gradually increased to 10 amperes. Under these conditions, a glass sample could be completely volatilized in about 1 minute.

Line intensities were estimated on a 1–10 scale, and, since the relation between line intensity and quantity of element present is a logarithmic one, the higher numbers in the scale represent very much greater quantities of elements present in the glasses than do the lower numbers in the scale. The absolute amounts of the various minor elements present have not been calculated, since, for the purpose of comparisons between glasses, only relative amounts, referred to a common scale, are necessary. The figures in Table 3 incorporate corrections which eliminate the factors of varying exposures and excitations. These corrections have been estimated by correlating the intensity of the silicon lines with the known relative silicon contents of the glasses.

TABLE 3

SPECTROGRAPHIC ANALYSES OF NATURAL GLASSES

Glass	Fe	Ca	Ti	Ni	B	Zr	Na	Mn	V	Co	Pb
Macedon (light)	2*	7	6	6	7	4	3	6	6	3	5
Macedon (dark)	6	6	8	8	6	3	5	8	5	7	4
Darwin (dark)	5	6	8	6	6	3	4	6	4	6	5
Darwin (green)	5	5	8	5	6	3	2	6	6	6	3
Artificial (sediment fused)	6	6	8	6	7	4	6	7	5	7	5
Australite (core)	5	10	9	5	6	4	5	9	6	7	3
Australite (flange)	5	10	9	5	6	4	5	9	6	7	6
Meteor Crater	2	6	4	9	6	3	2	3	7	1	3
Henbury	6	7	8	4	7	4	5	10	6	7	4
Libya	1	8	5	1	7	4	3	3	6	1	3
Fulgurite (N.S.W.)	2	5	5	2	5	4	3	4	6	1	5
Obsidian (N.Z.)	5	7	6	3	5	3	8	10	5	5	5
Pelée's hair	7	10	9	7	6	2	8	10	7	8	3
Tachylyte (Colac)	7	10	9	7	5	3	9	10	5	8	5

* Figures represent line intensities from 1 (very faint) to 10 (very strong).

DISCUSSION

The minor-element composition of a glass depends primarily on the composition of the source material and secondarily on the extent to which original trace elements have been removed, or added to, during the fusion process.

Since none of the glasses examined shows any trace-element associations that are unusual compared with the trace-element associations commonly found in terrestrial rocks, there is no obvious reason to suppose that any of them are of extraterrestrial origin.

In such examples as the Libyan, fulgurite, and Meteor Crater glasses, the high silica content makes it probable that they were derived from highly siliceous sedimentary material; but neither the

silica content nor the trace-element content of the other glasses, set out in Table 3, throws any light on the question of whether their source materials were of sedimentary or of igneous origin.

In only one instance does the trace-element table show a peculiarity that can be correlated with a feature characteristic of the mode of origin of the glass. The high nickel content of Meteor Crater glass, considered in relation to the high silica of the material and its low content of other minor elements, suggests that the glass originated during meteoritic impact, the nickel having been introduced from a nickel-iron meteorite as it struck and fused relatively pure siliceous material.

The amount of nickel recorded in the dark variety of Macedon glass is high enough to lend support to the suggestion that this material might come into the category of "impactites," but there is little certainty in such a deduction, especially as the sample of Henbury glass used (known to have been produced during meteoritic impact) proved low in nickel. The fact that much less nickel was recorded in the lighter- than in the darker-colored variety of Macedon glass does not influence the question either way, since, as apparently with Henbury glass, much of the glass formed by fusion on meteoritic impact could have escaped enrichment in nickel.

CONCLUSIONS

Examination of the nature, mode of occurrence, and chemical composition of various types of natural glass has not led to any finality regarding the origin of the Macedon glass from Victoria and the Darwin glass from Tasmania. Nevertheless, it has been shown that theories of origin suggested earlier are unlikely, whereas the discovery of soils and rock fragments fused under special conditions indicates the possibility that natural glass can develop during bush fires.

Macedon and Darwin glass are not glass meteorites (tektites) as australites, moldavites, bediasites, billitonites, etc., are believed to be. They do not show the form or surface features characteristic of the true tektites, many pieces having shapes like those resulting from the dripping, twisting, and drawing-out of solidifying glass. Moreover, they are far more vesicular and richer in silica than tektites, as well as showing other minor differences.

The glasses from Macedon and Darwin differ from fulgurites sufficiently to show that it is unlikely that they resulted from the fusion of sands by lightning. Whereas the glasses from Henbury, Wabar, and Meteor Crater show indisputable evidence of being true "impacttites," there is little that is suggestive of Macedon and Darwin glass having been formed by the fusion of sedimentary material by meteoritic impact.

There is nothing to indicate that Darwin glass originated from the fusion of rocks or their disintegration products caught up in burning tree trunks, although from the chemical evidence there is a strong suggestion that this glass (and hence probably Macedon glass also) represents fused sedimentary material of terrestrial origin.

The distribution of the Darwin glass in Tasmania might be readily explained by assuming that the pieces represent residues from silica-bearing plants burned during a bush fire. Such a mode of origin, however, is partially discounted by a comparison of the chemical compositions of Darwin glass and of glass from wood ash (see Table 2). The potash content of Darwin glass is much too low, compared with that of "straw silica glass"; but the

discrepancy is not nearly so great when compared with a slag produced from boxwood charcoal in the suction gas plant. In this comparison, however, it is seen that silica, alumina, and titania occur in greater quantities in the Darwin glass than in that from boxwood ash, while lime and magnesia are much lower.

The fact that lechatelierite particles occur in the various types of artificial and natural glasses is no criterion for determining the mode of origin of any particular glass. They can be formed in a variety of ways. All that the lechatelierite particles indicate is that quartz was a constituent of the source materials, that fusion was rapid, that the heat was very intense, and that cooling was rapid.

The evidence accrued therefore leads to the conclusion that each particular occurrence of natural glass has to be considered individually. The presence of lechatelierite particles, comparisons of chemical and spectrographic analyses or physical properties for each glass, are, taken alone, insufficient to establish a specific theory of origin. Mode of occurrence and associated features have gone further toward establishing the mode of origin of certain of the glasses than any other type of evidence. This applies especially to Henbury, Wabar, and Meteor Crater glasses, for which, from the very nature of their occurrence alone, the meteorite-splash theory of formation can scarcely be disputed, and it is definitely known that fulgurites are formed by the fusion of sand by lightning. A definite mode of origin, however, cannot be conclusively assigned to Libyan glass, Macedon glass, or Darwin glass from either their manner of occurrence, their associated features, or their chemical composition, whether ascertained chemically or spectrographically. All that can be said of Darwin glass and Macedon glass with any certainty is that they represent sedimentary material that has been rapidly fused at high temperatures lasting for relatively short periods and that cooling was rapid. The heating agency, however, cannot be specifically stated. The evidence is against heating in the way that tektites were heated and against heating by electrical discharge, while there is little, if anything, to support the idea of heating by meteoritic impact. Some of the evidence points to the possibility of the heat of bush fires being sufficient, under set conditions, to form natural glass, not so much, perhaps, by the fusion and collection of the silica contained in silica-bearing plants as, more probably (as the chemical composition indicates), by the melting of silica-rich material caught up under special circumstances in burning tree trunks.

ACKNOWLEDGMENTS.—The authors are grateful to Mr. H. R. Samson for samples of the refused basalt and basalt soil from a burnt-out tree trunk at Mount Franklin in central Victoria and to members of the staff of the Geology Department, Melbourne University, for stimulating discussions on the probable modes of origin of the natural glasses.

POSTANORTHOSITE GABBRO NEAR AVALANCHE LAKE IN ESSEX COUNTY, NEW YORK

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ABSTRACT

Postanorthosite gabbro dikes have more than local significance in the eastern Adirondacks. Three such dikes, two of which are discordant, cut the Marcy anorthosite 40 miles southwest of those described by Buddington and more recently by Balk. Avalanche dike, the largest of the three, is described in detail. This dike displays a sinuous textural pattern that is ascribed to turbulent magmatic flow. Garnet is abundant and may comprise as much as 16 per cent of certain portions of the dike. This mineral appears to have developed as a consequence of the instability of hypersthene and magnetite in contact with anorthite. Field and laboratory evidence suggest that this reaction took place under conditions of thermal metamorphism. Objections to other modes of origin are stated.

INTRODUCTION

In the west-central part of the Mount Marcy quadrangle, Essex County, New York, a large gabbroic dike (Avalanche dike) clearly cuts the Marcy anorthosite. Studies made in recent years in other Adirondack localities indicate the existence of two gabbroic magmas, similar in mineralogy but differing in genetic relationships. R. Balk has shown that certain of the Adirondack gabbros are of approximately the same age as the anorthosite and have evolved from gabbroic anorthosite, "in statu nascendi."[1] A. F. Buddington[2] has described gabbro dikes in the Plattsburg-Willsboro quadrangles which unquestionably have intruded solidified anorthosite. A recent paper by Balk provides a stimulating discussion of the problem of gabbro-anorthosite age relations in the eastern Adirondacks. In reference to certain of the Plattsburg-Willsboro dikes he writes:

> The significance of these dikes is obvious. In at least one section of the anorthosite massif, truly gabbroic magma has been intruded into solidified anorthosite. The writer's conception that a series of evolutionary stages leads from gabbro "in statu nascendi" to large spherical gabbros cannot be generalized for the eastern Adirondacks. Even if there have been large gabbroic masses segregating and settling out from a soft crystal mush, not yet crystallized throughout, there has been intrusion by a seemingly identical magma.[3]

Inasmuch as Avalanche dike lies approximately 40 miles to the southwest of the intrusive gabbros of Trembleau Mountain, in the Plattsburg-Willsboro quadrangles (Fig. 1), postanorthosite gabbros apparently have more than local significance in the eastern Adirondacks.

Lying in the heart of the Adirondack wilderness, Avalanche dike can be reached only by a 5-mile walk along a trail leading from the Adirondack Loj, which is 9 miles by road from Lake Placid. As a result, references to the dike in the literature are somewhat sketchy and confusing. The various interpretations of the same dike are as follows: W. C. Redfield, in 1837, refers to "the great dyke of sienitic trap in Mt. Mc-

[1] "Structural Geology of the Adirondack Anorthosite," *Min. u. petrog. Mitt.*, Vol. XLI (1931), pp. 308–434.

[2] "Geology of the Willsboro Quadrangle, New York," *N.Y. State Mus. Bull. 325* (1941), pp. 49, 50, 53, 59–63.

[3] "Comments on Some Eastern Adirondack Problems," *Jour. Geol.*, Vol. LII, No. 5 (1944), p. 290.

Martin."[4] E. Emmons writes: "The dyke consists of the rock denominated syenite or hornblende and granular feldspar."[5] J. F. Kemp, after a rather detailed study of the area, reached the following conclusion:

Although when viewed from a distance this rock mass appeared as an undoubted dike, yet as soon as it was examined in a hand specimen on the spot, it was pronounced at once to be no true intrusion, but to constitute a shear zone, or zone of wall rock dynamically metamorphosed along a fault. Subsequent microscopic evidence has corroborated this view.[6]

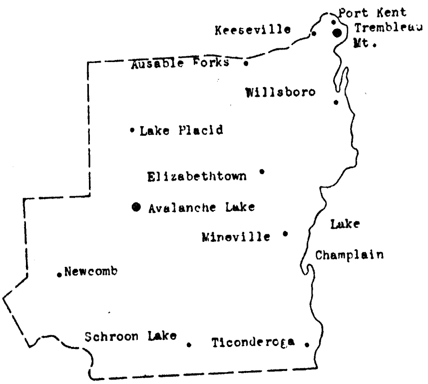

FIG. 1.—Guide map of Essex County, New York. Scale: 1 inch = 13 miles.

Kemp, who later described the geology of the Mount Marcy quadrangle, changed his original interpretation, writing: "Undoubtedly it entered as a large basic dike."[7] Recent field examination and petrologic studies indicate that the rock mass is a true discordant dike having strong mineralogical affinities with certain of the Plattsburg-Willsboro gabbro dikes.

GEOLOGY

Avalanche Lake lies in a narrow fault valley that strikes northeast-southwest, conforming with the major structural lines of the eastern Adirondacks. The lake is approximately $\frac{1}{3}$ mile long and drains to the southwest. It is one of the sources of the Hudson River. Avalanche Mountain to the northwest and Mount

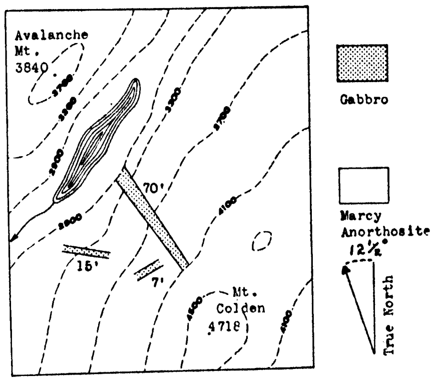

FIG. 2.—Outline map of the Avalanche Lake area. Scale: 1 inch = 1,320 feet. Broken lines are contour lines adapted from the U.S. Geological Survey topographic quadrangle map. The figures 70′, 15′, and 7′ indicate the thickness of each gabbro dike.

Colden (Mount McMartin) to the southeast are fronted by sheer fault-line escarpments which rise abruptly from the lake level. A prominent gorge cutting the Mount Colden escarpment has been formed by the partial erosion of the gabbro dike (Fig. 2).

The dike, which forms a wedge into Mount Colden, strikes N. 45°–55° W. and has a vertical dip. Along the contacts the foliation of the anorthosite ranges between N. 18° E. and N. 57° E. As such, the relations of gabbro to anorthosite are clearly discordant. The foliation of the

4 "Some Account of Two Visits to the Mountains of Essex County, N.Y.," *Amer. Jour. Sci.*, 1st ser., Vol. XXIII (1837), p. 301.

5 "Geology of N.Y. Part II. Survey of the Second Geological District," *N.Y. State Surv.*, 1842, p. 215.

6 "The Great Shear-Zone near Avalanche Lake in the Adirondacks," *Amer. Jour. Sci.*, 3d ser., Vol. XIV (1892), p. 109.

7 "Geology of the Mount Marcy Quadrangle, Essex County, New York," *N.Y. State Mus. Bull.* 229–30 (1921), p. 51.

anorthosite is enhanced by large oriented phenocrysts of plagioclase in a fine protoclastic groundmass. In the dike two sets of cross-joints strike respectively N. 10°–34° W. and N. 58°–82° E. Slickensides with a thin mineral veneer frequently characterize the northwest-southeast joint faces. The striae on these pitch 32° NW. Joint sets in the anorthosite strike respectively N. 23° W. and N. 70° E.

FIG. 3.—Avalanche dike, viewed from across Avalanche Lake. The steep-walled gorge was produced by differential erosion of gabbro.

Contacts of the dike with the walls of anorthosite are sharply defined, a feature accentuated by differential erosion (Figs. 3 and 4). Along its contacts the dike exhibits strongly foliated amphibolitic zones 1–2 feet wide. In places a narrow mylonitic zone appears between the amphibolitic rock and the anorthosite. The mylonitic zone is composed of crushed anorthosite containing streaks of the amphibolite. This foliation always parallels the contacts and is regarded as a secondary structure produced by movement along the contacts of the already consolidated dike. Further evidence for such movement is represented by occasional slickensides, coating the walls of the anorthosite. The striae on these slickensides pitch 33° NW.

FIG. 4.—Differential erosion of gabbro. A small stream may be observed flowing in the contact zone. Approximately 100 feet above lake level, looking southeast.

Emmons states that the dike can be traced up Avalanche Mountain. He writes:

> After going up three or four hundred feet of this latter mountain [Mount Colden], the dike can be traced up by eye to near the summit of Mt. McIntyre [correctly Avalanche Mountain] by two parallel cracks or fissures, which appear from this distance about two feet wide.[8]

[8] P. 215 of ftn. 5.

Kemp,[9] using this description, extended the dike across the lake on his geologic map of the Mount Marcy quadrangle. The present writer, after examining the rock on the opposite side of the lake, found only anorthosite. If the dike actually does extend into Avalanche Mountain, it would seem to have been offset since it was formed. The width of the dike at lake-level (70 feet) and its absence across the lake (a distance of approximately 80 yards) are perhaps indicative of lateral movement in a north-east-southwest direction. If the faulting that produced Avalanche Pass is correctly interpreted by Kemp as pre-Cambrian, the dike must be regarded as a postanorthosite gabbro of pre-Cambrian age. Kemp refers to "another dike of this same character nearly 3 miles to the northwest of Avalanche dike and with a parallel strike and dip. . . . . Apparently two intrusive masses entered the anorthosite along similar lines of weakness."[10] The writer has not been able to locate this dike, despite three separate trips to the area. Kemp[11] intimates that the position of this dike was not accurately plotted, and this seems to be the case.

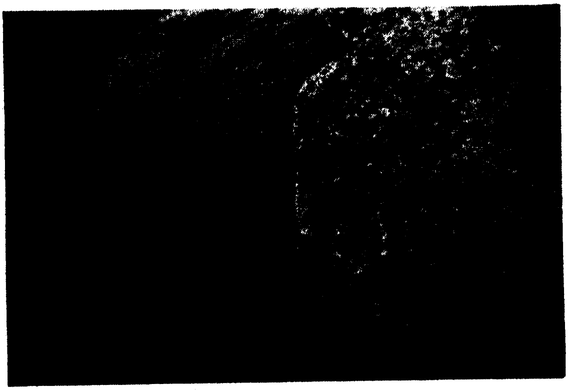

FIG. 5.—Concordant gabbro dike showing sharp contacts with anorthosite

Two additional gabbro bodies hitherto not mentioned in the literature were found cutting the anorthosite on Mount Colden. One of these is exposed approximately $\frac{1}{4}$ mile southwest of Avalanche dike. This dike also exhibits discordant relationships with the anorthosite. Several Brunton readings taken here show that the anorthosite foliation strikes N. 3°–12° W. The dike strikes N. 72° W. and has vertical dip. A prominent set of joints in the gabbro strikes N. 63° E., and a subordinate set strikes N. 8° W. This dike is 15 feet wide and of indeterminable length. Its northwesterly extent is hidden by vegetation, and its southeasterly extension is covered by debris from an avalanche that occurred in September, 1942. Amphibolitic and mylonitic border phases are again in evidence, and this dike is regarded as being of the same age as its larger neighbor to the northeast.

On one of the bare-rock exposures about $\frac{1}{4}$ mile below the summit of Mount Colden a third gabbro dike is exposed. This body, unlike the others, is parallel to the foliation of the anorthosite, which strikes N. 57° E. The contacts are ex-

[9] For geologic map of the Mount Marcy quadrangle, see ftn. 7.

[10] P. 51 of ftn. 7.

[11] P. 51 of ftn. 7.

ceedingly sharp, but there has been no differential erosion (Fig. 5). This dike is 7 feet wide, its continuation again being hidden by vegetation. A crude foliation in the gabbro strikes N. 12° E. The amphibolitic and mylonitic border phases are not represented, nor is there any evidence of movement along the contacts. Despite the concordant relations, this gabbro body is so similar in mineralogy and texture to Avalanche dike and exhibits such sharp contacts with the anorthosite that it is regarded as another postanorthosite gabbro.

MINERALOGY

Avalanche dike is composed of plagioclase, augite, hypersthene, garnet, hornblende, serpentine, titaniferous magnetite, orthoclase, biotite, and scapolite.

The plagioclase has a maximum refractive index of 1.552 and a maximum extinction angle of 22°, measured on albite twins. The axial angle is large, and the mineral is positive. This would place it in the andesine range or slightly on the sodic side of this plagioclase.

Although most of the andesine is strained, considerable variation may be noted even in adjoining grains. Some are twinned and unstrained; some show bent lamellae and cross-twinning; while others are untwinned and exhibit a marked undulant extinction.

A considerable amount of the plagioclase is antiperthitic, containing small quantities of scattered orthoclase. For the most part, these blebs of potash feldspar are unoriented with respect to the plagioclase twinning. Kemp states:

> The dike is peculiar in the amount of orthoclase which it contains. There is enough to make one hesitate whether to class it with the basic syenites or the basic gabbros. . . . . No statistical measurements have been made but the rock is obviously much like the gabbros rich in orthoclase. . . .[12]

Actually, the orthoclase content is not very high. Spectrographic analysis indicates that the K_2O content is between 0.5 and 1.0 per cent.

Clinopyroxene is usually next in abundance. It has the optical properties of augite, with

$$n_\gamma = 1.720,$$
$$Z \wedge c = 44°,$$
$$2V = 50°–60°.$$

In thin section the mineral is pale green and nonpleochroic. It occurs in subhedral grains, the borders of which are usually corroded.

Hypersthene is also abundant and displays a marked pleochroism from pink to green. This mineral has

$$n_\gamma = 1{,}730,$$
$$Z = c,$$
$$2V = \text{approximately } 45°.$$

Its refractive indices indicate 25 per cent FeO or 40 per cent $FeO \cdot SiO_2$.[13] As with the augite, discrete grains are mostly subhedral, with the edges modified by corrosion.

Garnet is an important component and may comprise as much as 16 per cent of a particular sample. The composition of this mineral was roughly determined by spectrographic analysis on grains carefully selected from the crushed material. Because of the fineness of grain size it was difficult to select many clean grains; and the analysis indicates, by the presence of a small amount of Na_2O, that a trace of feldspar may have been present. The percentages are as follows:

[12] P. 51 of ftn. 7.

[13] E. S. Larsen and H. Berman, "The Microscopic Determination of the Nonopaque Minerals, "*U.S. Geol. Surv. Bull. 848* (2d ed., 1934), p. 193.

$MgO > 10$	MnO 0.5–1.0
$Al_2O_3 > 10$	Na_2O 0.1–0.5
$SiO_2 > 10$	TiO_2 0.03–0.08
$FeO + Fe_2O_3 > 10$	V_2O_5 0.01–0.05
CaO 1.–5.0	$CuO < 0.01$

Apparently the garnet is low in the grossularite and andradite molecules. In the hand specimen, this mineral has a light-red color. In thin section and in fragment, it has a pale pinkish cast and a refractive index of 1.780. Occasional birefringent spots are due to included material rather than to strain. Discrete grains tend to be subhedral and are corroded like the pyroxenes. Apparently the garnet of this dike, as in many occurrences in gabbroic rocks, belongs to the almandite clan.

Of particular interest is a fibrous to lamellar green mineral which is quite abundant in the border phases of the dike. It has affinities with both serpentine and chlorite, but its appearance in thin section is more suggestive of the former. The mineral is slightly pleochroic from light-pink to green, is optically negative, and has

$$n_\gamma = 1.597,$$
$$Z = c, \text{ or } Z = \text{ near } c,$$
$$2V = \text{variable (usually near } 40^\circ).$$

The relatively high refractive index and the pleochroism may be due to a higher iron content than is normal for serpentine. Its appearance in thin section is suggestive of the bastite variety of serpentine so often found replacing enstatite and hypersthene.

Hornblende is present in widely varying amounts and is pleochroic from yellow-brown to dark greenish brown. Optically, it has

$$n_\alpha = 1.682,$$
$$n_\beta = 1.699,$$
$$n_\gamma = 1.702,$$
$$Z \wedge c = 9^\circ,$$
$$2V = 40^\circ–50^\circ, (-), r < v.$$

Titaniferous magnetite is always present in small amounts associated with the other mafic minerals.

Biotite is relatively scarce and is almost always associated with magnetite. It is strongly pleochroic from light to dark red-brown.

Scapolite, approaching Ma_{50}-Me_{50}, occurs only in the contact zone. This mineral is uniaxial negative, with $n_\epsilon = 1.544$ and $n_\omega = 1.568$.

Quartz, calcite, a small amount of pyrrhotite, and a confused mass of fibrous green material (serpentine?) are very late products, coating the slickensided joint planes.

PETROGRAPHY AND PETROLOGY

Undoubtedly, much of the confusion arising from previous descriptions of Avalanche dike is due to a lack of adequate sampling and statistical measurements. Kemp, who sampled only along the base of the dike, reports "slight variations in mineral composition" and goes on to state, "in aggregate, the dark silicates far surpass the feldspar."[14] Actually, the dike is not a particularly homogeneous mass, nor are the mafic minerals more abundant than the feldspars. This is well illustrated in Table 1, which gives the results of quantitative petrographic analyses of samples taken from various parts of the dike. Two methods of analysis were used on each sample in order to obtain a check on the results. Table 1, *A*, contains petrographic analyses made by the fragment- or grain-counting method. The specific counting techniques employed by the writer are those described in detail in a recent paper by F. Chayes. He summarizes the general procedure as follows:

(*a*) Collection of the original bulk sample, together with grinding and preliminary size reduction.

[14] Pp. 111–12 of ftn. 6.

(*b*) Final or micro-sampling, by which a few grains or a few hundred grains are reduced to a few milligrams, mounted and prepared for the count.

(*c*) Determination of the composition of the micro-sample.[15]

Table 1, *B*, contains petrographic thin-section analyses obtained by means of the Rosiwal method. By using two such widely different methods of analysis, the possibilities of error are greatly reduced.

Inasmuch as the dike rock has affinities with both the gabbro and the diorite groups, its classification presents a problem. An added difficulty is the disagreement among petrographic classifications concerning the division of the two groups. The classifications of both A. Johannsen[16] and F. F. Grout[17] require that the dominant plagioclase of a gabbro be more calcic than andesine. Grout notes, however, that approximately half the average gabbro is composed of mafic minerals, whereas the average diorites contain but 35 per cent of mafic minerals. In the case of Avalanche dike, the percentage of mafic minerals is always close to 50. According to S. J. Shand's classification,[18] the rock is a soda-gabbro. He uses the name "gabbro" for "the group of plagioclase-bearing rocks of mesotype to melanocratic character. It is divided, by the Ab:An ratio, into 'soda-gabbro' and 'lime-gabbro.' The name 'soda-gabbro' covers a group of rocks about which there has been little agreement in the past, some writers putting them in diorite, some in gabbro, and some making use of the noncommittal name 'gabbrodiorite.'" Johannsen also condemns the use of the name "gabbrodiorite." The present writer regards the association and the abundance of orthopyroxene and clinopyroxene in the dike as being of greater importance than the relatively low anorthite content of the plagioclase Of thirty-three modes of diorites, meladiorites, and melanocratic dioritic dike-rocks listed by Johannsen,[19] only 9 per cent contain this mineral association. Of sixty-seven modes of gabbros, norites, hyperites, melagabbros, and melanorites listed by the same author,[20] 25 per cent contain both pyroxenes. Grout also notes that augite diorites are less common than hornblende diorites and suggest a gradation toward gabbro. Balk, W. J. Miller, and other Adirondack geologists have included in the gabbro group rocks containing plagioclase nearer to An_{50} than

TABLE 1*

Sample No.	And.†	Aug.	Hyp.	Gar.	Hb.	Serp.	Mag.	Bio.
	A. Petrographic Analysis by Fragment-counting							
M.C. 1	51	20	12	15	....	....	2	....
M.C. 2	52	18	10	12	....	....	6	2
M.C. 3	57	12	3	1	5	17	3	2
M.C. 4	52	11	2	....	11	14	8	2
M.C. 5	52	14	20	5	....	....	6	3
	B. Petrographic Analysis by the Rosiwal Method							
M.C. 1	51	19	9	16	....	....	4	1
M.C. 2	52	19	11	13	....	....	4	1
M.C. 3	60	12	4	....	3	15	5	1
M.C. 4	54	9	2	1	12	13	8	1
M.C. 5	51	13	23	6	....	....	7	....

* M.C. 1, 2, and 5 are samples taken at various intervals (approximately 200-foot levels) near the center of the dike. M.C. 3 and 4 were sampled from the contact zone.

† Andesine containing orthoclase.

[15] "Petrographic Analysis by Fragment Counting," *Econ. Geol.*, Vol. XXXIX, No. 7 (1944), pp. 489–504.

[16] *A Descriptive Petrography of the Igneous Rocks*, Vol. III (Chicago: University of Chicago Press, 1937), p. 205.

[17] *Petrography and Petrology* (New York: McGraw-Hill Book Co., Inc., 1932), pp. 90–98.

[18] *Eruptive Rocks* (2d ed., London: Murby & Co., 1943), pp. 299–303.

[19] Pp. 154, 158, and 193 of ftn. 16.

[20] Pp. 217–19 and 241–43 of ftn. 16.

An_{60}. Buddington has classified many rocks of similar mineralogical composition as "metagabbro." Inasmuch as the rock of Avalanche dike is so similar in mineralogy to the Adirondack gabbros of other writers and since some of the anorthite of the original plagioclase may have gone into the formation of garnet, the present writer prefers to accept Shand's classification and assign this rock to the gabbro group.

Thin-section studies show no evidence of chilled border phases. The dike is a fine- to medium-textured rock throughout, with an average grain size of 0.3–0.5 mm. The texture is unusual and one of the most interesting features observed in favorable thin sections. The feldspars, which comprise slightly more than half of the rock, exhibit a granitoid texture with occasional elongated grains. In this mosaic of feldspar are masses, or "islands," of mafic minerals which are usually characterized by curved outlines (Fig. 6). Many of these take the form of lenses and reaction rims (Fig. 7). Microfoliation

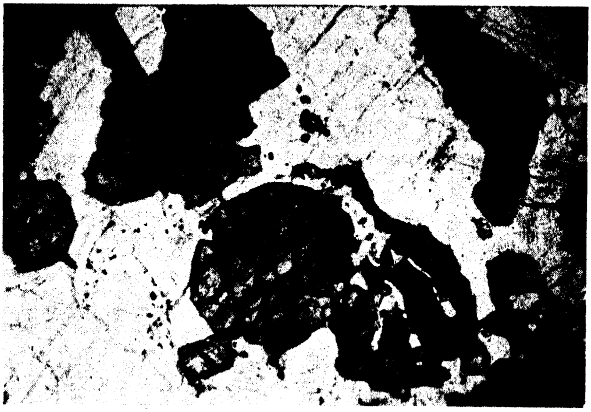

FIG. 6.—Mafic "islands" in a mosaic of feldspar. ×25, plane-polarized light

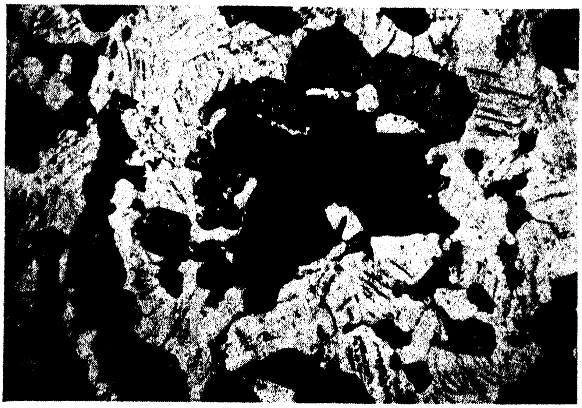

FIG. 7.—Imperfectly developed reaction rim. The core is magnetite and is succeeded by shells of biotite, hypersthene, andesine, and garnet. Quartz does not occur in these rims. ×25, plane-polarized light.

cannot be detected, nor can these mafic "islands" be resolved into the lenses which characterize mortar or augen gneisses. Examination under a low-power objective reveals a peculiar swirling effect, with the mafic masses often forming a crude concentric or sinuous pattern (Fig. 8). This textural feature is thought to be of primary origin. Apparently, variations in the viscosity and velocity of the magma, combined with flowage in a rough channel, gave rise to turbulent magmatic flow. Assuming that the flow of the magma continued until a late stage of crystallization, variations in the frictional resistance to flow in adjoining layers could have produced eddying and the resultant sinuous textural pattern peculiar to the dike. When the thin section is held up to a lamp, this textural feature becomes more apparent, since a greater area is observed at one time. Such a textural pattern does not appear to be compatible with dynamic metamorphism. It is more expectable that dynamic metamorphism would have induced some degree of granulation and recrystallization. This is well illustrated along the contacts of the dike, where deformation has produced narrow zones of strongly foliated amphibolite or mylonite.

Of particular interest are the hypersthene-augite relations. In thin section, grains with the same cleavage cracks may show the extinction positions of both pyroxenes, producing a peculiar mottled effect. In plane-polarized light the pleochroism of grains of this character at first suggests that they are composed entirely of hypersthene. The intergrowth is best observed on powdered material immersed in an index liquid and examined under high power. Here certain grains show strong evidence for the replacement of one pyroxene by the other. The clino-pyroxene forms embayments into the orthopyroxene and contains isolated remnants of the latter. These relations are illustrated in Figure 10.

Garnet, the other principal member of the mafic assemblages, often contains small inclusions of magnetite and hypersthene, an indication that these latter minerals contributed at least part of the FeO and MgO necessary for the formation of the garnet. The CaO and Al_2O_3 components could have been supplied by the anorthite of the plagioclase and possibly by augite. There is no necessity for the addition of silica, often implied or suggested by advocates of a late-magmatic origin of garnet in Adirondack gabbros. It is interesting to note that the garnet of Avalanche dike is an almandite, low in lime, perhaps an indication that most of the lime has gone into the formation of augite. Inasmuch as no introduction of material is required for the formation of the garnet, perhaps there is

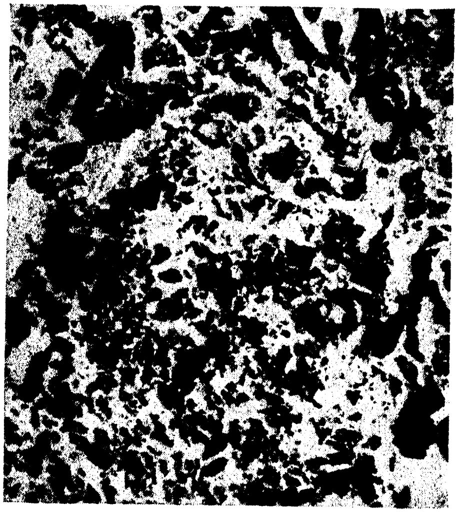

FIG. 8.—The sinuous textural pattern peculiar to Avalanche dike. The over-all swirling or eddying effect is an expression of turbulent flow. ×4.8, white light. The thin-section image was projected through an enlarger onto a negative.

a simpler explanation. Shand in a recent paper on coronas and coronites concludes:

The formation of coronas is a consequence of the instability of olivine (perhaps especially of iron-rich olivine) under the conditions of thermal metamorphism. The iron and magnesium ions discharged from the olivine attacked the anorthite of the plagioclase, generating either garnet or amphibole and spinel. The albite of the plagioclase, it is conceived, redistributed itself through the feldspar framework so as to keep the structure homogeneous.[21]

known to occur in the eastern Adirondacks. M. H. Krieger, in describing the dikes of the Thirteenth Lake quadrangle, notes that "some of the smaller, finer grained dikes are composed almost wholly of plagioclase and hypersthene."[23] The occurrence of garnetiferous gabbro dikes, similar in mineralogy to Avalanche dike, is reported from the same quadrangle. Garnet reaction rims also occur sporadically in the anorthosite of Mount Colden.

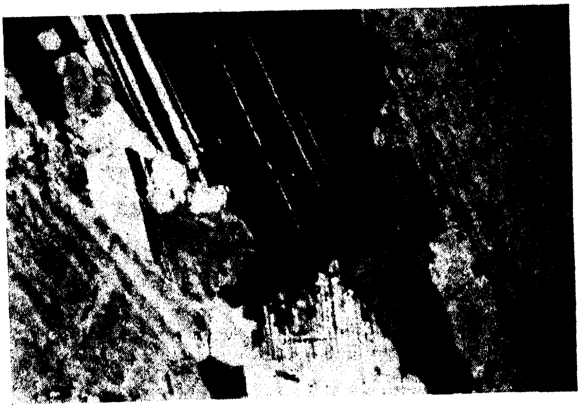

FIG. 9.—The Marcy anorthosite, showing the characteristic protoclastic structure. ×25, crossed Nicols

In the case of Avalanche dike, the unstable minerals were hypersthene and magnetite, rather than olivine. It is also noteworthy that the hypersthene is iron-rich. The refractive indices of this mineral indicate "25 per cent FeO = 40 per cent $FeO \cdot SiO_2$."[22] The residual plagioclase is close to An_{35}, rather sodic for the plagioclase of an average gabbro, and indicative of a loss in the anorthite through reaction with hypersthene and magnetite. This would indicate that the unmetamorphosed dike was of noritic composition. Dikes of this character are

This rock is composed of more than 90 per cent of feldspar (calcic andesine and a little orthoclase). The remainder of the rock is represented by titaniferous magnetite, hypersthene, hornblende, augite, apatite, quartz, garnet, and scapolite. Where garnet occurs, it usually forms reaction rims around hypersthene or magnetite. The abundance of garnet in the dike (originally a norite) and the sporadic occurrence of this mineral in the comparatively monomineralic country rock are regarded by the writer as indications of the relative susceptibility of these rocks to thermal metamorphism. The source of

21 "Coronas and Coronites," *Bull. Geol. Soc. Amer.*, Vol. LVI (1945), pp. 247–66.

22 Ftn. 13.

23 "Geology of the Thirteenth Lake Quadrangle, New York," *N.Y. State Mus. Bull. 308* (1937), p. 66.

the heat is not manifested by the presence of any postgabbro intrusives in the immediate vicinity.

Buddington, Kemp, M. Roessler, and others favor a dynamic or dynamothermal metamorphic origin of the garnet and the coronas. In the case of Avalanche dike, the evidence is decidedly opposed to a dynamic origin of this mineral.

With the exception of the narrow contact zones of amphibolitic and mylonitic rock, there is little or no evidence of granulation or any other expression of deformation in the dike. As previously stated, it would appear that dynamic metamorphism would not have produced the sinuous textural pattern characteristic of the gabbro. An examination of the narrow contact zones, where there has been movement and granulation, shows a preponderance of hornblende, serpentine, and scapolite. Garnet occurs very rarely in this zone, and the sinuous texture is replaced by a prominently schistose or mylonitic texture. Hornblende replaces augite; serpentine replaces hypersthene; and some of the plagioclase is replaced by scapolite. Similarly, the concordant gabbro dike near the summit of Mount Colden (Figs. 2 and 5), although devoid of marginal zones of amphibolite and mylonite, contains an abundance of garnet. Further evidence opposed to a dynamic or "regional dynamothermal" metamorphism lies in the well-developed primary foliation of the anorthosite. As has been shown, there is a marked divergence between the strike of the anorthosite foliation and any of the structures in the dike. If the stresses of any later period of deformation were such as to superpose a secondary foliation on the primary structure, the evidence is wanting.

To a "late-magmatic" or deuteric origin of the garnet and the reaction rims as postulated by J. L. Gillson, W. H. Calahan and W. B. Millar, H. L. Alling, R. C. Stephenson, and others, the author offers objections similar to those raised by Shand.[24] Late-magmatic reactions produce enrichment with silica and the alkalies and often produce myrmekite and micropegmatite. Evidence of these phenomena is lacking. Admittedly, the feldspar of Avalanche dike is antiperthitic and might represent an introduction of orthoclase into plagioclase. A simpler ex-

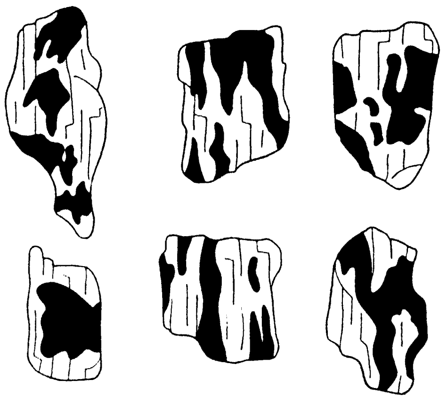

FIG. 10.—Augite developing at the expense of hypersthene. The dark areas represent hypersthene at extinction; the clear areas, augite. The sketches were made of fragments immersed in an index liquid.

planation, however, would appear to be unmixing, with orthoclase separating from solid solution in plagioclase.

In summary, the author wishes to emphasize that the conclusions reached in this paper apply only to the Avalanche Lake area and are not necessarily of regional import. A survey of the literature indicates that there has been too much generalization in the interpretation of eastern Adirondack geology. Inasmuch as the Adirondacks cover several hundred square miles, the extrapolation of local observations and interpretations is often unwarranted. The prime need is for

[24] P. 262 of ftn. 21.

more detailed field measurements and more representative sampling of outcrops. We find in the literature that "at least four-fifths of the igneous rocks of the Adirondacks have been deformed and more or less recrystallized and have flowed in the solid state."[25] Is there convincing evidence of this for so large an area?

ACKNOWLEDGMENTS.—The author is indebted to Dr. W. G. Valentine for critically reading the manuscript and pointing out certain inaccuracies and to Dr. Felix Chayes for making several helpful suggestions. The spectrographic analyses were made by M. J. Peterson and are here gratefully acknowledged.

[25] A. F. Buddington, "Adirondack Igneous Rocks and Their Metamorphism," *Geol. Soc. Amer. Mem.* 7 (1939), p. 252.

SAND FULGURITES WITH ENCLOSED LECHATELIERITE FROM RIVERSIDE COUNTY, CALIFORNIA

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ABSTRACT

Sand fulgurites from the vicinity of Indio, Riverside County, California, produced by the incomplete fusion of sand derived from granodiorite, contain fragments of lechatelierite formed by the more or less complete melting of some of the quartz grains. Some cristobalite is also present. The biotite grains have been completely fused to a dark-brown glass: the feldspars were, for the most part, melted to form a pale, almost colorless, glass.

INTRODUCTION

Among inanimate natural-history objects, few are more striking than fulgurites (L. *fulgur*, "lightning"), the curious glassy tubes formed by the fusion of sand by lightning. The term "fulgurite" has been extended to cover superficial coatings of glass produced from consolidated rock by the same agency, these being designated "rock fulgurites," to distinguish them from the more usual "sand fulgurites." A good general account of fulgurites with an extended bibliography will be found in the excellent paper of W. Fischer.[1]

In this country, sand fulgurites have been described from Massachusetts by E. Hitchcock,[2] from North Carolina by A. R. Leeds[3] and by J. J. Petty,[4] from South Carolina by Merrill[6] and Petty,[4] from Florida by J. S. Diller,[5] and G. P. Merrill,[6] from Illinois by Merrill,[6] from Maine by W. S. Bayley,[7] from Wisconsin by W. D. Shipton,[8] from New Jersey by W. L. Barrows[9] and by W. M. Myers and A. B. Peck,[10] and from Michigan by A. F. Rogers.[11]

MEGASCOPIC DESCRIPTION

For the fulgurites described in this paper I am indebted to Mr. W. Scott Lewis, mineral collector and dealer of Hollywood, California. They were obtained from a prospector, who would not divulge the exact locality but stated that they were from the region around Indio in Riverside County.

The specimens are more or less hollow,

[1] "Blitzröhren aus den miocänen Glassanden von Guteborn bei Ruhland, Ober Lausitz," *Neues Jahrb. f. Min., Geol. u. Pal.*, Beil. Bd. Vol. LVI, A (1928), pp. 92–98.

[2] "Fulgurites or Lightning Tubes," *Amer. Jour. Sci.*, 2d ser., Vol. XXXI (1861), p. 302.

[3] "On a Fulgurite," *Proc. Acad. Nat. Sci. Phila.*, 1874, p. 145.

[4] "The Origin and Occurrence of Fulgurites in the Atlantic Coastal Plain," *Amer. Jour. Sci.*, 5th ser., Vol. XXXI (1936), pp. 188–201.

[5] "Fulgurite from Mount Thielson, Oregon," *Amer. Jour. Sci.*, 3d ser., Vol. XXVIII (1884), pp. 252–53.

[6] "On Fulgurites," *Proc. U.S. Nat. Mus.*, Vol. IX (1886), pp. 83–91.

[7] "A Fulgurite from Waterville, Maine," *Amer. Jour. Sci.*, 3d ser., Vol. XLIII (1892), pp. 327–28.

[8] "A Note on Fulgurites from Sparta, Wisconsin," *Proc. Iowa Acad. Sci.*, Vol. XXIII (1916), p. 141.

[9] "A Fulgurite from the Raritan Sands of New Jersey, with an Historical Sketch and Bibliography of Fulgurites in General," *School of Mines* [Columbia] *Quarterly*, Vol. XXXI (1909–10), pp. 294–319.

[10] "A Fulgurite from South Amboy, New Jersey," *Amer. Min.*, Vol. X (1925), pp. 152–55.

[11] "A Review of the Amorphous Minerals," *Jour. Geol.*, Vol. XXV (1917), p. 526.

somewhat branching, irregular, cylindrical objects of medium-gray color, varying in length from 6 cm. to a maximum of about 30 cm. and in diameter from $\frac{1}{2}$ cm. to about 2 cm. Figure 1 is a photograph of a typical specimen; the cross sections are circular or nearly so, as shown in Figure 2. They have a superficial resemblance to the roots of certain plants. On the exterior, colorless and white to dark-brown sand grains are visible. A broken surface shows sand grains imbedded in a gray vitreous glass, and more or less spherical cavities lined with a lustrous glass. A rough determination of the specific gravity of an inch-size piece of fulgurite gave 2.01, which is obviously low because of cavities.

FIG. 1.—Sand fulgurite from the region around Indio, Riverside County, California. Natural size

The sand grains are angular to subangular, with a size variation ranging from 15 microns (μ) up to about 75 μ, but are mostly between 30 and 50 μ. Among the identified minerals of the sand are quartz, orthoclase, microcline, plagioclase, biotite, magnetite, a little zircon, and rock fragments (a grained igneous rock). The sand, which shows little sign of any sorting, was apparently derived from a granodiorite or similar rock.

I was familiar with sand fulgurites, produced from quartzose sand, which consist largely of lechatelierite[12] or silica glass. On noting the relatively large amount of ferromagnesian minerals (biotite) I concluded that there would not be any lechatelierite in thin sections of the Riverside County fulgurites, but I was agreeably surprised to discover that many quartz grains had been wholly or in part converted into lechatelierite.

Figure 2, a low-power photograph of a section of one of the fulgurites normal to

[12] "Lechatelierite" is the name given to the silica glass of fulgurites, meteor craters, and inclusions of volcanic rocks by Lacroix ("La silice fondue considérée comme minéral [lechateliérite]," *Bull. Soc. fran. de min.*, Vol. XXXVIII [1915], pp. 182–86).

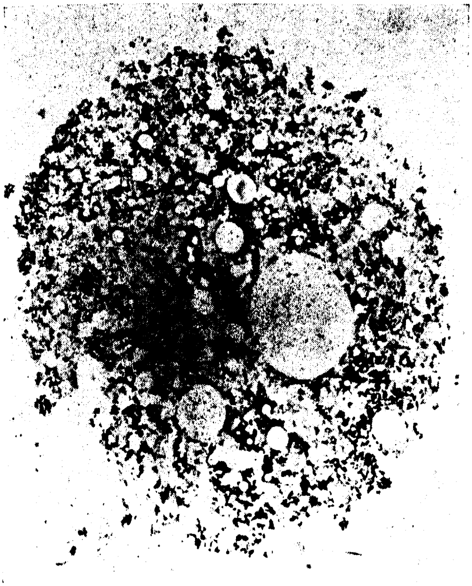

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 2.—Cross section of sand fulgurite showing general features. ×8.

FIG. 3.—Thin slide of sand fulgurite showing groundmass of dark to pale brown glass with circular sections of spherical vesicles and imbedded sand grains, which are more or less fused to silica glass. ×50.

FIG. 4.—Thin slide of sand fulgurite (an area different from that of Fig. 3), showing shattered quartz grains penetrated by silica glass. ×50.

FIG. 5.—The same area as that shown in Fig. 4, but taken with crossed Nicols. ×43.

the length, gives a general idea of its structure. The nearly circular sections of the vesicles point to the absence of any appreciable flowage. The writer[13] in recent years has considered lechatelierite to be a mineraloid rather than a mineral proper. The useful term "mineraloid" was proposed by J. Niedźwiedzki[14] for amorphous mineral-like substances.

MICROSCOPIC DESCRIPTION

General relations.—Figure 3 is a photomicrograph of a thin section (SMC 9) of one of the fulgurites. The dark areas represent almost opaque glass, produced by the fusion of biotite, which has a melting point of 1,050° C. The groundmass, or main portion, of the section is a pale-brown to almost colorless glass, produced largely by the melting of the feldspars. The index of refraction of the glass varies from about 1.510 up to about 1.550; the variation is evidently dependent upon the iron content. Some of the sand grains are intact; but most of them are more or less shattered, and on the borders many are melted.

Figure 4 shows another area in the same section. The angular unsorted quartz grains have been shattered, and in the larger grains silica glass has penetrated along the cracks. Figure 5 is the same area but taken between crossed Nicols. Here the silica glass appears isotropic.

Lechatelierite.—The first thin section made of the Riverside County fulgurite is shown in Figure 6. This small section was made to identify the isotropic fragments observed. The colorless grain marked with an arrow proved to have a refractive index of 1.457 ± 0.003. With a Wratten E22 screen being used in lieu of sodium light, this determination was made upon the unmounted section mentioned by employing successive immersion liquids after cleaning the section with xylol and drying each time. This is undoubtedly lechatelierite, or silica glass, produced by the fusion of a sand grain of quartz. This is the first noted occurrence of lechatelierite in the state of California.

The central part of the photomicrograph of Figure 3 is shown in enlargement in Figure 7. Some of the quartz grains have been completely melted to form lechatelierite. The equant central grain and the large crescent-shaped one near the center were partially melted but contain relict quartz, as shown by the difference in relief of the interior.

Cristobalite.—Figure 8, also made from section SMC9, shows near the center an equant grain of quartz which has been converted in part into cristobalite. Around the border of the grain the curved structure so characteristic of cristobalite is apparent. It also shows very weak nonuniform birefringence with a red-I-order plate. This central grain contains relict quartz, which does not show well in Figure 8 but is brought out in the photomicrograph (Fig. 9) of the same area taken with crossed Nicols. In the thin sections it is often difficult to distinguish cristobalite from the lechatelierite.

Nothing resembling tridymite was found in any of the sections.

Newly formed product.—In several of the thin sections small amounts of minute acicular crystals were observed. Some of these resemble feldspars, but they could not be identified with any degree of certainty.

[13] Rogers, A. F., *Introduction to the Study of Minerals* (3d ed.; New York: McGraw-Hill, 1937), p. 324.

[14] "Zur mineralogischen Terminologie," *Centralbl. f. Min. Geol., u. Pal.*, 1909, pp. 661–63.

FIG. 6

FIG. 7

FIG. 8

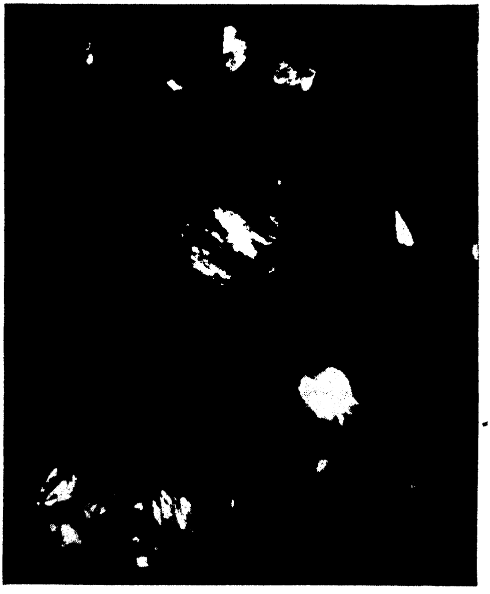

FIG. 9

FIG. 6.—Fragmentary thin slide of one of the sand fulgurites temporarily mounted in a liquid with n = 1.480, showing on the left margin lechatelierite (n = 1.457). The microscope tube is raised to show the Becke line. ×200.

FIG. 7.—Enlarged view of area at the center of Fig. 3, showing quartz grains altered in part to lechatelierite. ×123.

FIG. 8.—The large grain near the center has been altered on the exterior to cristobalite. The other grains are altered in part to lechatelierite. ×100.

FIG. 9.—The same as Fig. 8, but taken with crossed Nicols to show relict grains of quartz. ×92.

DISCUSSION

The incomplete fusion of the sand derived from granodiorite may be explained by the extreme rapidity of a lightning discharge. According to my colleague, Professor Joseph S. Carroll, director of the Ryan High-Voltage Laboratory, lightning discharges take place in less than 100 microseconds (a microsecond being one-millionth of a second).

The temperature reached in the partial melting of the sand was probably in the neighborhood of 1,800° C. According to R. B. Sosman,[15] quartz may be melted at 1,400° C. if sufficient time is given, but the rapid melting requires a temperature of about 1,800° C. Variation in temperature is evidently due to differences in electrical resistance from point to point.

The examination of the thin sections gives evidence of some diffusion in the glass of the goundmass but little evidence of any flowage. The circular sections of the vesicles are in marked contrast to the elliptical vesicles of volcanic rocks.

[15] "Silica as a Refractory in the Steel Industry," advanced paper read before the American Iron and Steel Institute, New York, May 24, 1929 (p. 24).

BOTTLE SPRINGS

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ABSTRACT

Submarine fresh-water springs along the shore of the Stansbury Peninsula, Great Salt Lake, are described. Their geologic, biotic, and cultural significance is discussed. Similar occurrences in other areas are mentioned.

INTRODUCTION

During the progress of field work on the Stansbury Peninsula, Great Salt Lake, Utah, fresh-water springs totally surrounded by saturated salt water were found in many places. These springs are perennial, many having a substantially constant outflow and a few being subject to marked seasonal variations.

The name "Bottle Springs" was applied to them because of an ingenious method of securing drinking water. Local ranchers submerge a corked empty bottle in the salt water of the lake; lower it until the mouth is directly over the fissure or sand boil from which the water issues; then remove the cork. When the bottle is filled, the cork is reinserted and the bottle removed from the lake. The recovered water is either "fresh" or so slightly brackish that it is still potable.

GEOLOGIC ENVIRONMENT

Although environmental conditions are not always identical, every bottle spring found was near shore, usually located in an embayment in the shoreline supersaturation tufa, and was close to either a known fissure or a clearly recognizable delta deposit. Fissure springs predominated, and in many cases the water had a pronounced sulphurous taste and cathartic action, suggesting a magmatic origin (hot springs are numerous in this area). Delta springs are usually slightly brackish, probably because of leaching of old shoreline deposits; and most have pronounced seasonal variations in discharge.

The geologic environment of a fissure-type bottle spring is shown in Figure 1. Arrangement of geologic components of a delta-type bottle spring is too obvious to need an additional diagram.

In most instances, bottle springs can be "spotted" from shore by the presence of matted growths of intensely green algae a few feet below the lake surface. Such algal growths are not present in the saturated waters of Great Salt Lake.

As embayments are present in the shoreline tufas wherever they are close to bottle springs, it may be concluded that dilution of lake brines by inflow from the springs inhibits tufa formation—an inference in general accord with chemical theory.

BIOTIC FEATURES

All of the bottle springs found in the Salt Lake Basin support luxuriant growths of fresh-water algae; and in the algal masses are numerous diatoms, all of common modern types, normal to the present environment.[1] Thus, the finding of fresh-water diatoms in tufas deposited by the lake at any stage should not be in-

[1] This is worthy of note, as the lake has had no surface connection with any body of fresh water outside of its drainage area for at least 10,000 years and has been saline for much or all of that time.

UPLAND TERRACES IN SOUTHERN NEW ENGLAND: A DISCUSSION

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American Association for the Advancement of Science, Washington, D.C.

ABSTRACT

Analysis of methods and data utilized by George F. Adams to demonstrate that multiple terraces of marine origin do not exist in southern New England reveals that, despite the inadequacy of Adams' criteria, Barrell's thesis has been supported rather than disproved.

In the September issue of this *Journal* George F. Adams[1] attempts to set aside much of the definitive geomorphic work which has been done in New England during the last twenty-eight years. Claiming that "Joseph Barrell's recognition of broadly developed multiple terraces of marine origin is shown to be erroneous, since the existence of the terraces was concluded from incomplete evidence and questionable logic," he invites scrutiny of the evidence and logic which he employs to dismiss the painstaking field and laboratory studies of Hatch, Barrell, Bascom, Knopf, Pond, Meyerhoff and Hubbell, and Rich in his sweeping conclusion: "Multiple terraces of a regional nature do not exist."

Adams' conclusions are founded primarily on a study of "multiple projected profiles" (or "zonal profiles," as the present writer prefers to call them), supplemented both in the laboratory and in the field by the application of criteria which have such limited utility as to be worthless in solving the problems under consideration. Inasmuch as Adams confines himself to a critique of the marine-terrace hypothesis advocated by Barrell, the present writer will likewise limit his discussion to this aspect of the subject, notwithstanding the fact that Adams, as noted above, also attempts to set aside the terrace concepts of all recent workers who have analyzed the New England upland.

It should first be noted, however, that Barrell's marine hypothesis was shown to be inapplicable in western Massachusetts and in Vermont nearly seventeen years ago. Pond[2] and Meyerhoff and Hubbell[3] found clearly defined fluvial terraces of regional extent at vertical intervals which made correlation with Barrell's terraces in Connecticut conclusive. The fluvial pattern of the terraces so identified and correlated is unmistakable. These cyclical surfaces are evident enough in the broad upland surfaces of central and western Massachusetts, but they form striking benches in the upstream reaches of the Westfield, Mill, Deerfield, West, and other rivers tributary to the Connecticut. In these upstream sections individual terraces are present in different watersheds on different rocks and in the same watershed on different rocks, and different terraces have been preserved within the same watershed on the same rocks.

In subsequent field work Olmsted and Meyerhoff have traced terraces in

[1] Pp. 289–312.

[2] A. M. Pond, "Preliminary Report on the Peneplanes of the Taconic Mountains of Vermont," *16th Ann. Rept. Vt. State Geol. Surv.* (1927–28), pp. 292–314.

[3] H. A. Meyerhoff and M. Hubbell, "The Erosional Landforms of Eastern and Central Vermont," *16th Ann. Rept. Vt. State Geol. Surv.* (1927–28), pp. 315–81.

Connecticut, within the area described by Barrell and by Adams; and it must be stated that Adams' claim of close relationship between terraces and geologic structure and rock composition is an unwarranted generalization based upon specific cases but ignoring the more numerous exceptions. Only the exceptions are critical, for structural and lithologic controls are obvious where they exist; and they have been noted by every worker. It behooves Adams to explain the situations where no such controls can be demonstrated.

In order to dispose of the marine hypothesis, Adams sets up as the only criteria for recognition of elevated marine surfaces two closely related types of features: (1) "cliffs whose marine origin is adequately attested by the presence of wave-cut notches, sea caves, and stacks" and (2) "high-level benches which abut against steep cliffs." The latter, in his opinion, are valid only "if they bevel the structures and have considerable areal extent." These criteria instantly rule out recognition of some of the raised marine terraces along the California coast, concerning the origin of which no competent worker has any doubt; and they are entirely adequate to eliminate almost every elevated marine surface that has undergone subaerial modification. They are fatal to the ancient, fluvially dissected, and glaciated land forms of southern New England.

No conclusion can have greater value than the criteria on which it is based, and it is evident these two criteria are inapplicable and hence valueless when used to support a negative conclusion. Fortunately, additional criteria are available from the most elementary principles of shore processes and shoreline erosion and of fluvial dissection of raised marine surfaces. For example:

1. Waves plane surfaces which, in general, parallel the shoreline.

2. Headlands occupying interstream positions are planed first, and rocks in valley or lowland situations are affected only if the headlands are worn back to approximate alignment with the valley outcrops.

3. Despite appreciable adjustments to major lithologic and structural features, wave planation is effective on all lithologic types to a degree not matched by any other erosive agent.

4. Wave-cut terraces are graded surfaces, steepest inshore, where the slope may be as high as 90 feet per mile for the first mile planed.

5. Raised marine terraces acquire consequent drainage, which, in general, flows normal to the abandoned shoreline.

6. Such drainage, especially if it is extended consequent, may exhume filled valleys in which compaction of the fill creates depressions of post-emergent age.

7. Fluvial dissection proceeds most rapidly in two directions: parallel to the slope along the consequent and extended consequent streams; and normal to the slope in the inner lowland and in other subsequent lowlands, where a coastal-plain veneer has covered the wave-planed surface.

8. Upon removal of coastal-plain deposits, drainage will make normal use of subjacent nonresistant rocks and other lines of weakness.

These are by no means the only universally recognized features available as criteria in analyzing Connecticut's upland surfaces, but they will suffice for sound conclusions which bear little resemblance to those reached by Adams. An examination of Adams' map (Fig. 10) will illustrate the odd use which has been made of facts. Every contour up to and including 600 feet parallels the shoreline,

whereas the contours at 700 feet and above conform with the drainage pattern. Coincident with the break between the 600- and 700-foot contours is a complete change in the character of the interstream surfaces and in the adjustment of the drainage. At 700 feet and above, the topographic texture is finer than at lower levels, and terrace relief is relatively high; below 700 feet the texture is coarse, and the interfluves are flat and young. At 700 feet and above, streams and local relief features are adjusted to structure; below, such adjustments are few. These contrasts are so clear in the field as to be photographable.

As further evidence of Adams' ill-considered use of facts, it must be noted that he cites (pp. 301 and 304) a valley separating flat ridge crests at 680–700 feet from the next higher level at 940 feet as evidence that Barrell's marine hypothesis is wrong. This valley, with others similarly located, is one of the best supports the marine hypothesis has. Where else but in this precise location could the excavation of an inner lowland take place? This phenomenon has been employed by adherents of the theory of regional superposition to locate former marine features in New York and New Jersey, but across the state line in Connecticut the feature unaccountably changes its meaning.

Adams' methods of work cannot go without challenge. The present writer has in his laboratory collection complete sets of profiles for all New England. They include projected, zonal, and linear types, each one of which has its appropriate objective use. The zonal type employed by Adams is not so infallible as he would have his readers believe. For example, there is only one orientation in a single locality in which the seemingly uniform slope shown in Figure 8 (p. 306) from 600 feet to Long Island Sound can be registered in a zonal profile. Elsewhere profiles of all types reveal a composite surface, in which the separate terrace components, though variable in width, are relatively narrow. Inevitably they register best when they are profiled at right angles to their greatest linear dimension, and poorest when the angle approximates 45°. In consequence of the curvature of the Connecticut shoreline near the New York boundary, north-south zonal profiles are ill-adapted to show what is there. Yet Adams would have his readers believe that the blind use of a single compass direction is the only objective method of work, forgetting that nature determines the compass directions of all geologic operations and that any attempt on the part of a researcher to set them is not only arbitrary but subjective. In the case under consideration the choice of north-south orientation is perfectly designed to obscure the features which are present, and the writer must question whether that is a legitimate aim of research.

A similar result is achieved in Adams' generalized contour map (Fig. 10), in which he selects a 100-foot interval to demonstrate that terraces do not exist. Only a few of the upland surfaces are separated by vertical intervals as great as 200 feet; hence Adams' selection is ideally designed not to show what he is trying to prove is not there. It is easy to make a case when such methods are employed, but the case made cannot be accepted as a scientific conclusion. Even so, the marked contrast between the marine-planed and the fluvially dissected portions of southern New England stands out on the map but is completely ignored by its author.

In view of the inadequate criteria se-

lected, the inadequate use made of them and of available facts, the employment of techniques which cannot show features whose existence the author intends to disprove, and the failure to make full and proper use of the exhibits introduced in support of his conclusion, Adams' charge that Barrell used "incomplete evidence and questionable logic" is all the more extraordinary. Hatch, Barrell, Bascom, Knopf, Pond, and Hubbell and Meyerhoff may not have agreed on the origin of the upland terraces in New England and the Piedmont; but their disagreement is in part due to the fact that each concentrated his attention on different portions of the upland. What is significant is their unanimous agreement on (1) the presence of erosional terraces, (2) the approximate vertical positions and correlation of the terrace forms, (3) their independence of structure and lithology over broad areas, and (4) their genetic relation to changing levels of land and sea. Adams has offered nothing which disposes of these basic points and nothing which modifies them in any way. In so far as his materials are usable, they support Barrell's thesis instead of proving it erroneous, as he thinks.

REVIEWS

Dana's System of Mineralogy, Vol. I: *Elements, Sulfides, Sulfosalts, Oxides*. 7th ed. By CHARLES PALACHE, HARRY BERMAN, and CLIFFORD FRONDEL. New York: John Wiley & Sons, Inc., 1944. Pp. xiii+834; numerous figures. $10.00.

Under the rule of Timothy Dwight (1795–1817) the great days of Yale began, if only because he established professional schools there. Meanwhile, he destroyed all vestiges of the free regime of Ezra Stiles, the liberal republican lover of Jefferson and the French. Much as he hated popery, he hated Voltaire and Rousseau still more, and he wished to restore the world of Jonathan Edwards; and gone were the days when the Yale students called themselves Paine, Hume and Turgot and paid more homage to Man than they paid to Jehovah. No more dancing, plays, cakes and ale. But, together with other studies, science, long prominent in the college, to which Sir Isaac Newton had presented his works, spread rapidly with the help of President Dwight .... he discovered Benjamin Silliman and made him a professor (1802), the man who took the black art of chemistry out of the hands of the necromancers and planted it squarely in the schoolbooks. It was Silliman who popularized the discoveries of Lavoisier, and multitudes of Americans learned that earth contained fifty ingredients, that air was made up of two gases and that water was a compound. He popularized mineralogy and geology also, and the students began hunting specimens instead of bears and foxes, while ladies set up on their mantelpieces bits of marble, ore and quartz. If not exactly a golden age, this was a new age at least that began, for America, at Yale [from pp. 82–83 of the currently popular *World of Washington Irving* by Van Wyck Brooks].

Silliman, best known, away from New Haven, as a popularizer of science and the founder of the *American Journal of Science*, was succeeded in 1850 at Yale by his son-in-law and former student and assistant, James Dwight Dana, who had graduated in 1833 and who had prepared the first edition of his *System of Mineralogy* in 1837. The second edition (the first to be published by Wiley) appeared in 1844. In the fifth edition (1868) Dana was aided by G. J. Brush, who prepared a first appendix; later appendixes were by the son, E. S. Dana, who wrote the sixth edition (1892), together with its first appendix; W. E. Ford collaborated on the second appendix, and alone wrote the third one (1915).

The present edition is a *Dana* only for sentimental reasons; it is an entirely new work in every sense except that it necessarily embraces that part of the old *Dana* which has stood the test of time. It can conveniently be referred to as "Pabef I," from the first letters of the names of its authors. It represents the advances made in the science over a half-century, about the same period as was covered by all previous editions subsequent to the original volume. It has moved from Yale to Harvard, which appears to be about to go back to a relatively restricted college curriculum. While in no sense a college textbook, it is bound to have great influence on the teaching of the science, since one object of the university course must be to make the new *System* understandable. The completed work is to appear in three volumes: II, *Halides, Carbonates, Sulfates, Borates, Phosphates, Arsenates, etc.*, and III, *Silica, Silicates*.

Like the last edition, this one embraces an introductory section of 85 pages, followed by descriptive mineralogy. The Introduction (under fifteen headings) has a 32-page section on morphology and a 37-page general bibliography, divided into two parts. The extended section on morphology is largely devoted to an explanation of the mathematics underlying two-circle goniometry. The length of this may seem out of balance with the short space given X-ray crystallography or physical and chemical properties; presumably this is because the standard textbooks cover the first subject much less satisfactorily than they do the others.

Minerals are divided into classes, types, groups (series), and species; and numbers are assigned in line with this form of subdivision. The classes are as in the sixth edition, except that the oxides are subdivided into five classes; the uranates are in the second oxide class, and columbates-tantalates are put under the last class of oxides. Thus, the four families listed in the title for Volume I are treated in a total of eight classes. For example, hercynite (7212) belongs to class 7 (multiple oxides), type 2 (the AB_2X_4 type), group 1 (spinels), and is the second species listed under this group; there are

twelve species in this group; the last one, chromite, has the number 721·12. Similarly, smaltite (2·10·12) belongs with the sulfides (class 2), type 10 (AX_3), the first "group" (the skutterudite series), and is the second species listed in this category. Thus, chromite is seven-two-one-twelve; smaltite is two-ten-one-two. It would probably be simpler to use capital letters for classes and small letters for groups; this should be even truer for classes numbered 10 and higher that will appear in later volumes. Under this scheme chromite would be G2a12 and smaltite B10a2. In any case, it is a real improvement to get away from the serial system of numbers used in the sixth edition. However, since the details of classification will likely suffer changes, the new scheme of numbering should not be regarded as immutable.

The five classes of oxides are obtained by separating simple oxides from multiple oxides (in the same fashion that sulfides are distinguished from sulfosalts); and each of these is further subdivided into two classes, depending on whether the heavy metals of subgroups III–VIB of the periodic table are present or not. A fifth class includes hydroxides; it should be noted that hydrous oxides are present in all five classes. The eight classes covered in Volume I are divided into forty-three types, listed on page 87. Each of nine of these types contains less than five numbered species, and type 46 (p. 87) is not recognized among the numbered species (p. 491). The chapter in which the minerals of any one class are described starts off with a complete list of the species included in the sequence described. This shows the distribution among types and groups, as well as species numbers. In a few cases unnumbered (nonvalid) species are here listed, but generally they are not. The names of some of the unsatisfactorily defined species are farther indented. The names of minerals are shown in four manners in this volume. Boldface capitals are used for a well-defined species, even though it may be known from but a single locality. Lower-case boldface type is used for a species less well defined, yet sufficiently definite to warrant a species number. These names do not stand out well from those set in similar but larger type which are used to designate the descriptive headings. Lightface capitals are used for names of minerals which are not sufficiently valid as distinct species to warrant assignment of a number. If these appear before "**Ref.**," they generally refer to altered or impure samples of the previous species; if after "**Ref.**," they may be less closely related to the previously described species.

Following the species number appears the name, chemical formula, and the history of naming, with names in as many as five foreign languages, all of which are indexed. The various properties described are then set off clearly by lower-case boldface type. The use of adjectival prefixes, as advocated by Schaller, eliminates a great number of names used to describe chemical variations within a series—a most desirable practice.

Morphological properties are given in terms of the Goldschmidt two-circle method of goniometry, making use of the gnomonic projection; the polar axial ratio and the position angles appear in more than one orientation for certain systems. The angle tables, many of which represent research by Professor Palache and his students, include not only the standard polar co-ordinates of the known faces but also the angles between a given face and the several pinacoids or other axial faces. In many cases these tables have been calculated for a new orientation and/or axial ratio to fit the unit cell; the dimensions, angles, and contents of the latter (where known) are given; also, the transformation formulas and the space group. Those brought up on single-circle goniometry may miss the lists of interfacial angles present in the old *Dana*. However, if such an angle between two faces of a form parallel one axis is wanted, it can be obtained by doubling the complements of the ϕ-angles (prism zone) or doubling the ρ-angles (this last is not true for monoclinic or triclinic crystals). For other faces it is about as quick to make a stereogram (plotting over a net) from the given position angles and read the required angle as it is to look it up in the old volume.

Other items covered include habit, physical and microscopic properties, and chemistry. A few microscopic data on opaque minerals are presented. In the instances of many series, it would be desirable to have graphs relating physical properties and chemical composition. Even though these might be based on incomplete knowledge, they would help to bring order to the mass of data here included. Small optical-orientation diagrams would also make a desirable addition.

The section on occurrences has been modified so that more data on paragenesis (largely from Lindgren) and fewer on geographic occurrence are presented. This is a highly desirable change;

in general, mineralogists are behind economic geologists in the subject of genetic mineralogy. Alteration products, pseudomorphs, and synthetic species are described. Utilization is not covered. The derivation of the name is outlined, but it would be desirable also to indicate its pronunciation. Under each species appears a bibliography covering especially the recent literature (to 1941; in part through 1943), with critical annotations. There are numerous line-drawings, all of which have been redrawn or newly made for this volume.

It is impossible to thumb through this work without realizing what an outstanding contribution it is. The spirit throughout is not one just of compilation but rather one of research. Many gaps have been filled by re-examinations made in the course of the revision, and at other places need for further study is pointed out. The volume contains a surprising amount of unpublished material. It is a monumental work that fittingly climaxes the long years of experience of Professor Palache and the boundless enthusiasm of Berman and Frondel. It brings to poignant realism the great loss we have all suffered in the tragic death of Berman in a plane crash in Scotland in connection with a war project. It puts us under further obligation to two benefactors to whom the work is dedicated: R. A. F. Penrose and A. F. Holden. The publishers deserve great credit for using larger type and doing such an excellent job, celebrating their one hundred years' association with the *Dana* tradition; both they and the authors forego any profits until the Geological Society of America grant has been repaid. This work will continue to be the bible of the mineralogists, and it will be used often by petrologists and other geologists. Now that the war is over, we may hope for the early appearance of the other two volumes; the quality of the present one is so high that it will be difficult not to become impatient.

D. Jerome Fisher

"Molluscan Evidence of Pliocene Climatic Change in New Zealand." By C. A. Fleming. In *Transactions of the Royal Society of New Zealand*, LXXIV (1944), 207–19.

The theory that the existing thermal convection circulation in the ocean is abnormal and did not operate so as to cool the ocean in pre-Pliocene times receives some support from the evidence cited by Fleming of Miocene sea temperatures in the New Zealand region. He finds that many molluscan extinctions that occurred after the mid-Miocene affected genera and families "now confined to tropical and subtropical seas," whereas "in the Miocene the New Zealand area lay wholly within the subtropical zone of surface waters and there is no indication of faunal zoning due to hydrological differences."

Though in the Miocene the waters throughout the region were decidedly warmer than they are now, absence of reef-building corals "would seem to place an upper limit to any assessment of Miocene sea temperatures." Rather, therefore, than adopt the theory outlined above, the author prefers to suggest that the warmth of the Miocene sea may have been due to a southerly sweeping current of water of equatorial origin in a South Pacific system of surface currents comparable to that of the present day. Against this it might be argued, however, that the Notonectian current, which now warms New Zealand coastal waters and is, incidentally, responsible for the importation of eastern Australian mollusks, has quite probably come into existence only in later times, for the author himself dates the introduction of such forms only as latest Pliocene to Recent, though the efficiency of the list of species in the Recent fauna of late derivation from East Australian sources is now of imposing length.

Post-Miocene changes are summed up thus: "Faunal changes in the New Zealand Pliocene suggest that late Tertiary lowering of sea temperatures reached its peak in the mid-Pliocene," and "New Zealand mollusca did not suffer changes commensurate with the severity of the Pleistocene glaciation." The author, however, rejects the hypothesis (proposed by F. W. Hutton in 1872) that the glaciation of New Zealand took place in the Pliocene. Refrigeration was foreshadowed, nevertheless, by a northward spreading of cold water in the Pliocene, for analysis of faunal trends indicates that the cold waters advanced until in the middle of the Pliocene they reached as far as latitude 40°.

In contrast with mid-Pliocene conditions, absence of cold-water mollusks has been noted in the late Pliocene and in post-Pliocene times, and Pleistocene lowering of temperature of the New Zealand coastal waters by as much as 4° or 5° C. is regarded as quite out of the question. "Among the marine mollusca the only case of Pleistocene due to a cooling climate is of an

inter-tidal form vulnerable to low air temperatures." The curious absence of molluscan evidence of the presence of cold waters is explained by assuming that an approximation to the present-day surface circulation of ocean water had been established in the late Pliocene and Pleistocene, that the warm Notonectian current was as warm as it now is, and that the line of its convergence with the subantarctic water of the west wind drift was as far south. "The conception of New Zealand in the Pleistocene as a land of frigid meteorology set in relatively temperate seas" is thus arrived at. "Advance of cold waters northward in the Pliocene would have culminated in the Pleistocene (when air temperatures reached their minimum) had not the Notonectian current begun to operate as a purely local South Tasman influence and to blanket New Zealand seas from further cooling after the mid-Pliocene."

The author's arguments which show that the Notonectian current "commenced to operate in the uppermost Pliocene" support the suggestion made above by the reviewer that Miocene warmth was not the result of mere local protection from invasion by Antarctic waters but was part of a world-wide Tertiary mildness of ocean-water temperatures.

C. A. COTTON

Geology and Manganese Deposits of Northeastern Tennessee. By PHILIP B. KING, HERMANN W. FERGUSON, LAWRENCE C. CRAIG, and JOHN RODGERS. (Tennessee Department of Conservation, Division of Geology, Bull. 52; prepared in co-operation with the U.S. Geological Survey.) Nashville, 1944. Pp. 275; pls. 8; figs. 35.

This report describes the occurrence and origin of manganese ores in the five northeastern counties from which three-fourths of the Tennessee production has come. The region lies partly in the southeastern edge of the Appalachian Valley and partly in the mountains that border it on the southeast.

Most of the deposits are associated with the Shady dolomite which is usually without fossils but in a few places carries Lower Cambrian fossils. A few small deposits occur in the immediately overlying and underlying formations. About half the production comes from the mines in Bumpus Cave.

Larger features of the geology that are of interest are the unbroken stratigraphic sequence, 20,000 feet in thickness, from the base of the Cambrian into the Ordovician and the several low-angle thrust faults that have been deformed by later folding.

The Shady dolomite is the oldest of the thick carbonate deposits of the Paleozoic section in the Appalachians. It generally occupies valleys or coves between the mountains; and because it weathers readily, most of these areas are occupied by residual clays from its decay, and outcrops of fresh dolomite are uncommon. Where unweathered, blue dolomite is the commonest rock type, but white dolomite also occurs. It is noteworthy that the dolomite passes sharply, though irregularly, along the strike into limestone. It is inferred that dolomitization took place after original limestone was deposited. The dolomite shows partial recrystallization, whereas the limestone does not. Silica in the form of jasperoid has also replaced parts of the dolomite; and in places bedding, oölitic texture, and the outlines of dolomite rhombs are preserved as relict structures in the jasperoid. In a broad way the jasperoid seems to be most abundant in areas of considerable deformation. Analyses of the fresh dolomite show from 0.3 to 2.59 per cent of manganese carbonate.

Weathering has blanketed the Shady dolomite with an irregular covering of residual clay. This is usually thin on the lowest slopes near the present streams and thickest on certain divides that represent older valley floors. Below the clays the dolomite shows the irregular, pinnacled surface characteristic of residual decay of carbonate rocks. Exposed surfaces of the residual clays are altered to a depth of 6 feet or more to a red mealy soil resulting from the leaching of the more soluble components of the clay.

The commercial manganese deposits carry the manganese in the form of oxides and hydrous oxides, psilomelane and cryptomelane, and the softer pyrolusite and wad. The hard oxides occur as nodules, show a concentric or radiate structure, and have developed through gradual replacement of the clay.

The manganese deposits are not evenly distributed in the residual clays from the Shady dolomite but have a spotty distribution. They are most likely to be found in areas nearest the underlying Erwin formation and in the higher ridges. Individual deposits usually cover less than 2 acres. At least one part of manganese oxides to twenty parts of Conde clay is necessary for workability. The maximum total yield

from any single ore-body has been less than 4,000 tons of concentrates, and most deposits have yielded less than 1,000 tons.

Production reached the peak of 9,268 long tons in 1940 and declined to 3,231 in 1942. Total production to the end of 1942 was 55,519 long tons.

EDSON S. BASTIN

Geology and Manganese Deposits of the Glade Mountain District, Virginia. By RALPH L. MILLER. (Virginia Geological Survey Bull. 61.) Charlottesville, 1944. Pp. 150; pls. 19; figs. 20.

This report, prepared by the U.S. Geological Survey, deals with the Virginia continuation of the manganese deposits of northeastern Tennessee. The deposits lie in southwestern Virginia on the southeast side of the Appalachian Valley, bordering the Blue Ridge province. The mines were operated during World War I and again during World War II, as a result of curtailed imports of manganese ore.

As in northeastern Tennessee, most of the manganese ores are in residual clays derived from the Shady dolomite. The manganese is believed to have been originally disseminated as carbonates through the lower part of the Shady dolomite, especially in the beds within 300 feet of the base. The manganese oxides were deposited in the clay in disseminated form or grew, layer on layer, replacing the clays to form nodules. No evidence of hydrothermal processes in their formation was found.

Plate 2 is an instructive physiographic diagram of the manganese-producing area. Plate 1 is a geologic map of the area in the scale of 2 inches to the mile.

EDSON S. BASTIN

General Meteorology. By HORACE ROBERT BYERS. New York and London: McGraw-Hill Book Co., Inc., 1944. Pp. x+645; figs. 300. $5.00.

Horace Byers is our pioneer in the writing of textbooks in modern meteorology. He broke new ground in 1937 with his *Synoptic and Aeronautical Meteorology;* and his *General Meteorology,* though it acknowledges its derivation from its author's earlier textbook, is also, as is claimed by its author and publishers, "a new book." What is more, it is a new kind of book; for to my knowledge no one author has heretofore tried to write a textbook that presents, on a fairly advanced level, a broad survey of the theoretical and empirical matter that makes up modern meteorology. The adjective "general" in its title is aptly chosen. Most of the book is couched in terms calculated to appeal to readers who are seeking scientific insight rather than instrumental mastery of a technique. It is obvious that the author of such a book requires more intellectual maturity than does one who writes with a less "general" aim. Byers' maturity is immediately evident in the admirable organization and smooth development of most of his theoretical discussions. The reader sometimes wishes for a more felicitous phrasing of a sentence, but linguistic faults are far less prominent than in much recent American meteorologic writing.

The contents of the twenty-four chapters of "General Meteorology" can be grouped into the following three categories: (1) deductive discussion of atmospheric physics, most of which falls into two divisions: (*a*) the thermodynamics of the atmosphere and (*b*) its dynamics; (2) description of atmospheric phenomena in terms (such as the names of circulation structures and fronts) that are devised specially to characterize these phenomena; and (3) application of insights gained through (1) and (2) to practical problems of weather forecasting and aviation. That such a cleavage still exists in a first-rate textbook is evidence that atmospheric phenomena are still too refractory to be treated wholly inductively; if they were completely amenable to physical theory, there would be no need for the second of the three categories enumerated. That Byers has not pretended to fit all his data into a Procrustean bed of theory should commend his book to the readers of this *Journal,* who are accustomed to working with materials that resist the sharp tool of physical theory even more stubbornly than do meteorologic phenomena.

These readers want and need to know something about meteorology. Many of them have been bewildered by the feverish bustle that has afflicted American meteorologic circles in recent years. Byers' book is the first one that can be heartily recommended to them as a summary of modern knowledge of the atmosphere. This commendation should not be construed as a suggestion that the reader lay aside his critical spectacles when he picks the book up. Some controversial and some questionable passages are

included in it and are not always plainly labeled as such. The critical reader can usually distinguish, however, between what is rigorously demonstrated and what is generalized from limited evidence.

The book has some formal blemishes, too; such as are apparently unavoidable in a work of its magnitude, but most of them are minor; good will and careful reading usually suffice to extract the meaning intended. The reader encounters the most flagrant blemish early. Figure 1 (p. 6) purports to show graphically the variation through the year of the height of the noonday sun above the horizon at Washington, D.C. The ordinates of the curve are, alas, computed for a latitude of 51° north, the complement of Washington's 39°.

JOHN LEIGHLY

Geology for Everyman. By SIR ALBERT SEWARD, with Preface by SIR HENRY LYONS. Cambridge: Cambridge University Press, 1944. Pp. xi+312; figs. 10; pls. 8. $3.25.

Geology has need for a middle class between the expert and the ignoramus. For a long time, in Britain at least, there have been many amateurs who find delight in prying into the geology of their environs, making collections, or viewing parts of their country with geologic understanding. Occasionally some important discovery has resulted from these hobbies. Yet, among amateur naturalists, those devoted to geology have for some reason been less numerous than those interested in flowers, birds, and insects. Because geology can furnish greater attractions than most people realize to anyone who enjoys a walk over the countryside, Sir Albert Seward has written this little book to show others the way to the same enthusiasm which he has experienced over a long lifetime. The manuscript fortunately was completed three days before his sudden death.

Assuming that many readers will have slight acquaintance with the subject, the author first develops elementary principles and necessary facts preparatory to his systematic unfolding of British geology. His main purpose is then accomplished with the help of a series of journeys through the British Isles, which supply much of the material used to build and illustrate the historical story. Simple significant observations are made and fitted together properly, and from these the reader is led logically to the interpretations and conclusions which geologists have reached. Interest is aroused through the observations, imagination is stimulated by the methods and results, and the study becomes easy.

Reversing the chronological order, Seward starts with the latest chapter of the geologic history and works backward to the pre-Cambrian, which is the end of the journey. Ice action, volcanic activities, marine inundations, desert conditions, diastrophic paroxysms, and other happenings are revealed in their appropriate places in these journeys through space and time. As might be expected from the special researches of the author, plant and animal fossils yield abundant eloquent testimony throughout the greater part of the study. This book should serve its purpose by making geology inherently interesting and readily understood, through skilful presentation, without lowering its level by overpopularization.

R. T. C.

Geological Map of the Dominion of Canada. Map 820A. Ottawa: Canada Department of Mines and Resources, Mines and Geology Branch, Bureau of Geology and Topography, 1945. $0.50.

This map is published as two sheets, each 44×32 inches, at a scale of 1:3,801,600 (1 inch = 60 miles) on a Lambert conformal conic projection. The two sheets are designed to be mounted together to form a single map. But since each carries a complete marginal legend, they may be used separately.

The workmanship is up to the usual high standards of the Canadian Geological Survey. An excellent choice of colors, in good register and applied to a new base, depict the geology of the vast reaches of Canada in surprising detail. As might be expected, the detail varies from place to place and is greatest in the marginal parts of the Laurentian shield and in the southern and western parts of Canada in general. This reflects the greater knowledge of these more accessible and more important mineral-producing areas.

This map will be gratefully received by all interested in the advancement of geology on the North American continent.

F. J. PETTIJOHN

"The Geology of Banks Peninsula: A Revision, Part II: The Akaroa Volcano." By R. SPEIGHT. (*Transactions of the Royal Society of New Zealand*, Vol. LXXIV.) 1944. Pp. 223–54; 5 pls.; map.

Professor Speight's new account of the geology of the submaturely dissected basalt dome of the Akaroa volcano describes some interesting features that have previously escaped attention.

In an earlier contribution to the present series ("Part I: Physiography" [1943]), the author has described the dissected form of the volcano and reaffirmed statements made in still earlier papers regarding the erosional origin of the central hollow that is now Akaroa Harbor. The map and photographs accompanying the article here reviewed show the relation of this erosion caldera to the volcano as a whole—which the author terms a "cone" but describes as of domed form. It is nearly circular, with a diameter of 20 miles; and before the removal of the central part by erosion it reached an elevation (according to the author's estimate) of 5,000 feet above present sea-level. This is a maximum estimate, however, for it does not allow for a flatness of the summit which the author regards as probable.

Apparently younger and less dissected on the flanks than is the adjoining Lyttelton volcano (the two together make Banks Peninsula), this dome retains some of the original constructional form on flat-topped ridges.

A number of new analyses (by F. T. Seelye) of specimens collected by the author are quoted to show the predominance among the flow lavas of olivine basalt. The soda content of this is high, and a percentage of FeO ranging from 8 to 9.76 is consistent with the fluidity manifested by the numerous low-angle flows. The author has perhaps overestimated the proportion of pyroclastic material interbedded with these, for many scoriaceous surfaces of flows have been mistaken in the past for explosively ejected scoria beds.

As in the case of many oceanic-island basalts, differentiation in the direction of trachyte has resulted in the injection of dikes of this composition, and trachyte masses that occur as "mushrooming" expansions of the dikes are now described for the first time from this district. These present close analogies with similar forms on Ascension, St. Helena, and Maui (the recently described "bulbous domes" of Stearns) and are considered here to be, for the most part, extrusive rather than laccolithic.

C. A. COTTON

Elements of Geology for Western Australian Students. By E. DE C. CLARKE, R. T. PRIDER, AND C. TEICHERT. Perth: University of Western Australia Text Books Board; University Bookshop, Hackett Hall, Crawley, 1944. Pp. xii+301; figs. 117. 21*s*.

This book is an introduction to geology from the Western Australian standpoint. Processes effective in semiarid and arid regions are therefore emphasized, and metamorphism receives more than average consideration because of the extensive exposures of pre-Cambrian rocks in this portion of the continent. If the treatment of some of the more elementary phases of the subject seems rather brief, this is because students are expected to get fuller details from the reference readings at the end of each chapter.

Approximately the last third of the book is devoted to historical geology, which, appropriately, is the evolution of the Australian continent and the development of its life-forms, with references to other parts of the globe when particularly needed. Students of regional geology will find this a useful book.

K. T. C.

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NEPHELINIZED PARAGNEISSES IN THE BANCROFT AREA, ONTARIO

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ABSTRACT

Geological mapping in the Bancroft area has indicated that the nepheline-bearing rocks were developed in metamorphosed sediments of Grenville type. The visible granite-syenite complex adjacent to the nepheline rocks is younger and intrusive into those rocks. Some obvious paragneisses locally contain nepheline, and an increase or decrease in nepheline content may occur both along and across the strike of the gneisses. In fact, some rocks were traced from a typical calcareous mica or hornblende paragneiss facies into rock rich in nepheline and containing little calcite. It was also noted that the nepheline-bearing rocks are not everywhere closely associated with either granite or limestone; they actually occur scattered throughout a very heterogeneous series of metamorphosed sediments. There is no field evidence that reaction took place between a granitic or syenitic magma and limestone to yield a feldspathoidal magma; neither do the nepheline rocks present intrusive relations to the other rocks; nor are there segregations of lime-silicates in the immediate neighborhood, which might be expected if limestone syntexis in its commonly accepted form had occurred.

The proposed hypothesis is that the nepheline rocks are the result of a process of "nephelinization," in which certain impure calcareous sedimentary horizons were attacked and replaced by solutions from some unknown but probably granitic source, resulting in the deposition of nepheline and sodic plagioclase without the formation of an actual nepheline-syenite magma, which has been postulated by proponents of the syntexis theory. Most of the nepheline pegmatites also appear to be replacements, although their origin is more doubtful.

INTRODUCTION

This paper presents the results of nearly eight months of detailed field work in the Bancroft area of nepheline rocks, in 1941, when possible domestic sources of aluminum were being investigated. Because the rocks were being examined for an economic purpose, the extent and nature of the nepheline-rock bodies were ascertained far more precisely than ever before. Exact relationships have been determined which on earlier maps were, of necessity, generalized. The very nature of the work enforced close study of certain aspects which might normally have been neglected or inferred. Furthermore the use of diamond drills yielded informative data, and the hypothesis advanced herein may therefore be said to be built on three-dimensional, rather than on two-dimensional, knowledge.

A material part of the investigation was the preparation of numerous chemical analyses of both surface and depth samples. As it happened, expediency dictated partial analyses only, on a routine basis in most instances; but, notwithstanding the fact that few complete rock

analyses were made, a wealth of analytical data has been gathered.

Although the area examined in greatest detail is a relatively small part of the whole alkaline-rock district, nevertheless the work done therein and the examination of neighboring exposures suggest that the results are definitely applicable to the district as a whole. An exception is the Blue Mountain deposit, where very little work was carried out. However, in addition to the brief study by the authors in that locality, some information was obtained from engineers of the American Nepheline Corporation. Some discussion of the Blue Mountain deposit is therefore included in the appropriate places.

THE BANCROFT NEPHELINE-ROCK AREA

DEFINITION AND MAPPING

The village of Bancroft is situated some 75 miles north of Belleville, Ontario, in Faraday Township, Hastings County. The "Bancroft area" is defined for the purpose of this paper as that area lying immediately to the east of Bancroft and comprising lots 23–30 inclusive, in Concessions XIII and XIV of Dungannon Township, and parts of Hastings Road Lots 58, 59, 60, and 61 in Dungannon and Faraday townships.

F. Chayes[1] has discussed the importance of map scale in portraying the geology of this area; his map was prepared on a larger scale and is more detailed than earlier maps. The present geological map comprises a still smaller area on a still larger scale and thereby brings out still more detail. The information was originally compiled at a scale of 200 feet = 1 inch, used in plane-table surveying; unfortunately, reduction to the size presented here has resulted in considerable loss of detail. The original map, however, has already been published at a scale of 10 chains = 1 inch.[2]

The information obtained from the survey is presented here in three separate maps. These three are equivalent to the map already published, but, on account of the reduction in size, separation has been necessary. Figure 2 illustrates the topography, with various hills named for convenience of reference; Figure 3 shows the occurrences of rock outcrops; and Figure 4 indicates the contacts, determined and assumed. The delineation of the rock boundaries is considerably different from that offered by Chayes.[3]

From time to time it will be necessary to refer to rocks outside the Bancroft area as defined above, but the following sections will apply in the main to that area.

GEOLOGICAL SETTING

The Bancroft area forms only a small portion of a larger district, which comprises the two counties of Haliburton and Hastings. These counties, on account of their mineral occurrences and good exposures of early pre-Cambrian sediments and volcanics, have been studied in considerable detail. The general rock sequence for the district as a whole, including the Paleozoic limestones and other rocks on the southern edge of the area, is given in Table 1. This information was compiled from existing reports and from recent field work.

The rocks which constitute the group of paragneisses and crystalline limestone and dolomite are those commonly termed "Grenville." They are found as great bands in a terrain of predominantly

[1] "Alkaline and Carbonate Intrusives near Bancroft, Ontario," *Bull. Geol. Soc. Amer.*, Vol. LIII (1942), p. 468.

[2] James E. Thomson, "Mineral Occurrences in the North Hastings Area," *Ont. Dept. Mines, 52d Ann. Rept.*, Vol. LII, Part III (1943).

[3] Ftn. 1.

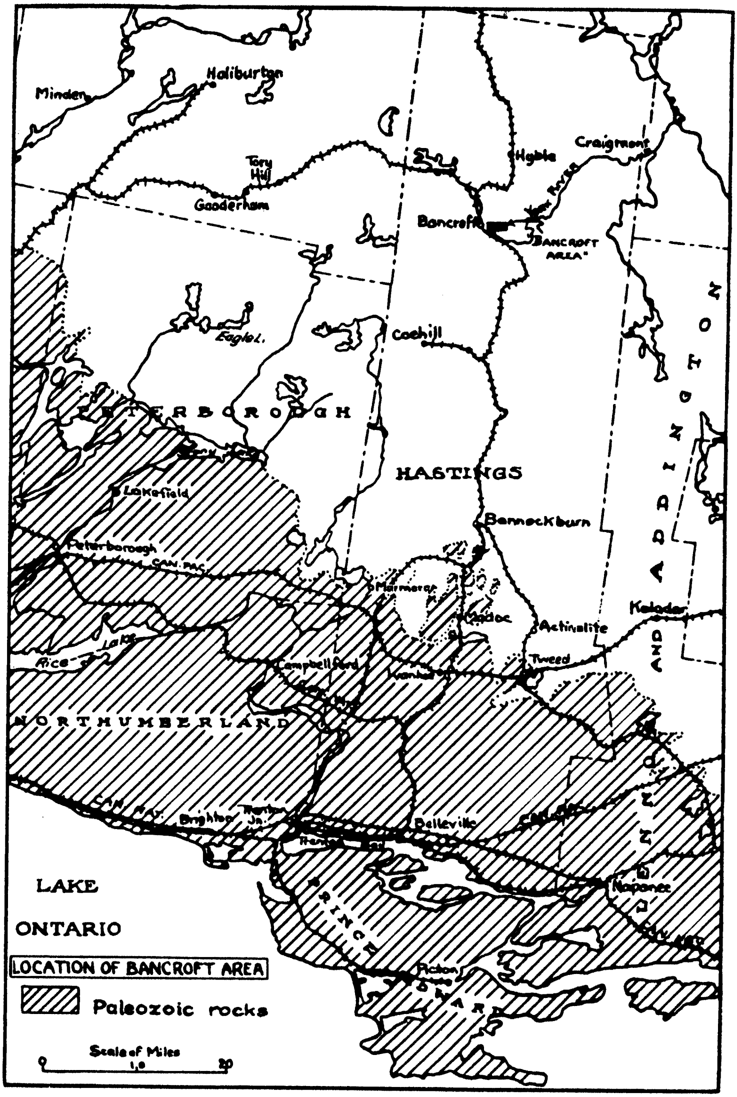

FIG. 1.—Index map showing location of Bancroft area

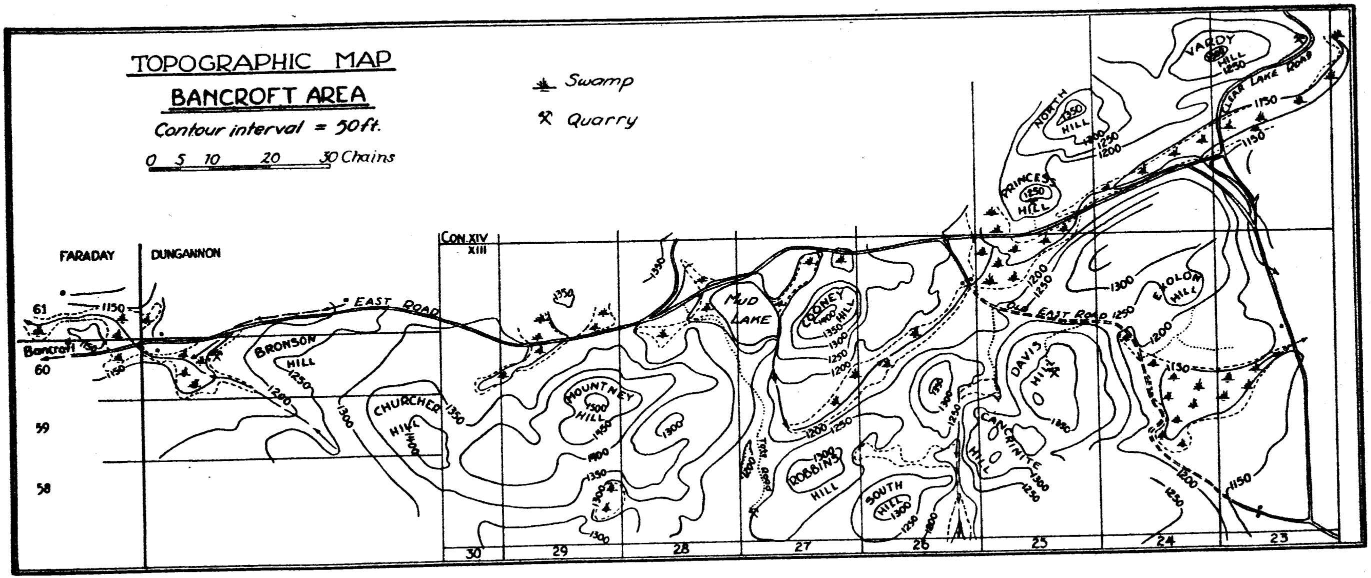

FIG. 2.—Topographic map of the Bancroft area

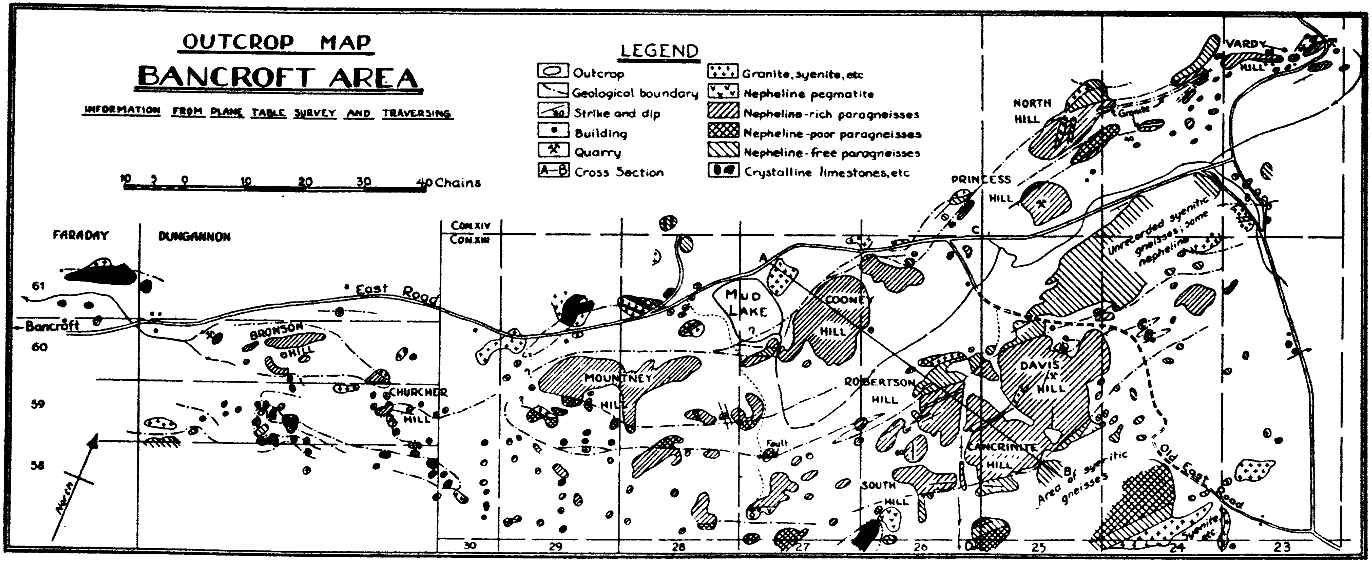

FIG. 3.—Outcrop map of the Bancroft area

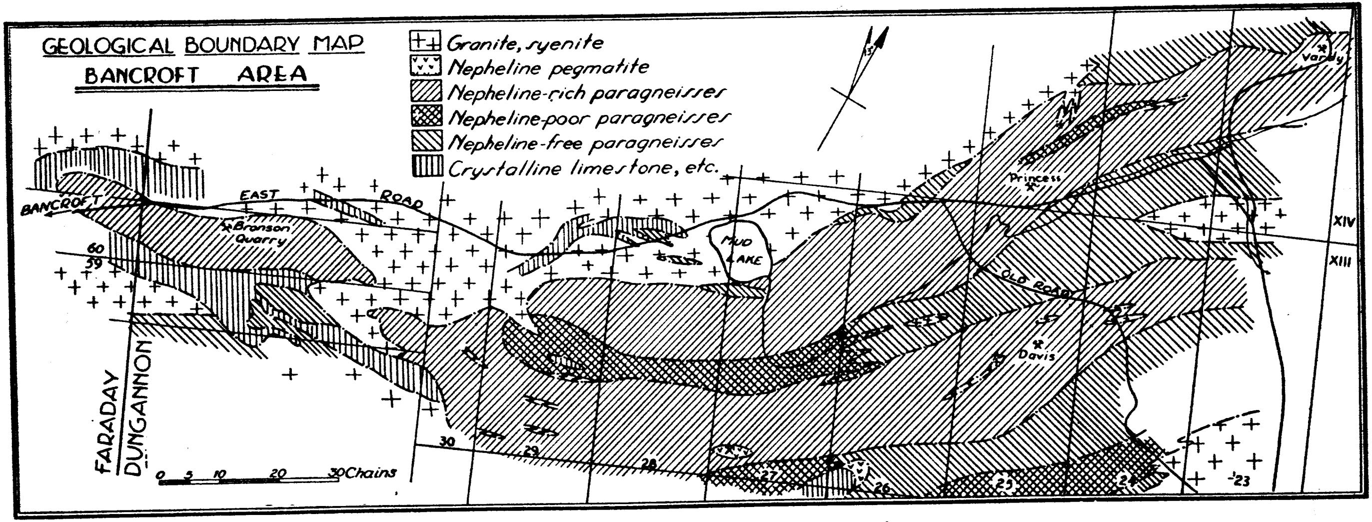

FIG. 4.—Geological boundary map of the Bancroft area

granitic gneisses and are intruded by several rock species, including granite. The nepheline-bearing gneisses, which are intimately associated with altered and recrystallized sediments of the Grenville type, were formed still later and were, in turn, invaded by syenite and granite. F. D. Adams and A. E. Barlow[4] recognized that the granite near Egan Chute, east of Bancroft, and the granite at Blue Mountain are younger than the nepheline rocks. M. L. Keith[5] came to the same conclusion for the Blue Mountain area and, indeed, believed that most of the granitic rocks of the nepheline-rock belt are younger. Recently Thomson[6] and J. Satterly[7] have recognized that the granitic rocks adjacent to the nepheline-bearing rocks are postnepheline, although Chayes[8] believes that the granites are either older or contemporary.

TABLE 1

GENERAL ROCK SEQUENCE, HALIBURTON-HASTINGS DISTRICT

Cenozoic	
Recent	Clay, sand, gravel, peat
Pleistocene	Clay, sand, gravel, boulders
Paleozoic	
Ordovician	Limestone, dolomitic limestone, sandy limestone, shale, arkose, quartzite*
Pre-Cambrian	Diabase
	Pink granite, syenite, and pegmatites
	Nepheline-bearing gneisses and pegmatites
	Granite, granite gneiss, hybrid gneisses
	Diorite, gabbro, anorthosite, peridotite
	Crystalline limestone, dolomite; amphibolite
	Conglomerate
	Micaceous and amphibolitic paragneisses, quartzite and graywacke
	Basic volcanics (hornblende schist, chlorite schist)*

* Ordovician rocks and Keewatin-type volcanics do not occur in the special area discussed in this paper.

The actual area of nepheline-bearing rocks is small, but they and the associated types occur in a more or less east-west, discontinuous belt, passing directly through Bancroft and possessing a total length of some hundred miles.

The bands and elongate bodies of the nepheline rocks conform to the strike of the associated rocks. Additional exploration may well bring to light more exposures and prove greater continuity to the belt.

The Blue Mountain deposit lies some distance south of the main belt, in Methuen Township near Peterborough.

PETROGRAPHY

LIME ROCKS

The lime rocks of the area vary from the relatively pure, coarsely crystalline limestone south of the Bronson Hill, through biotite-rich types and diopside-marbles, to an extremely impure amphibole-mica-calcite-feldspar rock, which not uncommonly carries nepheline or cancrinite. The minerals observed in the field and in thin-section studies are as follows:

calcite	dolomite
biotite	tremolite
albite	nepheline
oligoclase	garnet

[4] "The Geology of the Haliburton and Bancroft Areas, Province of Ontario," *Can. Dept. Mines, Mem. 6* (1910), p. 324.

[5] "The Petrography of the Alkaline Intrusive at Blue Mountain, Ontario," *Bull. Geol. Soc. Amer.*, Vol. L (1939), pp. 1795–1826.

[6] P. 9 of ftn. 2.

[7] "Mineral Occurrences in the Haliburton Area," *Ont. Dept. Mines, 52d Ann. Rept.*, Vol. LII, Part II (1943), p. 18.

[8] Pp. 497–98 of ftn. 1.

diopside	graphite
"hastingsite"	magnetite
muscovite	zircon
microcline	apatite
serpentine	spinel
cancrinite	

Besides the carbonates, the commonest minerals are the micas, diopside, the feldspars, and serpentine. Nepheline was observed in carbonate rocks in a few places, the most accessible exposure being in the railway cut in Bancroft village. There, steeply dipping gneisses include comparatively pure marbles and impure types, rich in silicate minerals and containing only small amounts of calcite and dolomite. Some of the rocks are similar to those earlier named "foyaite," "jacupirangite," etc.

Peculiar lime rocks are noticeable, such as the "flow marble"[9] below the sawmill on the York River in Bancroft, and the mylonitic facies on the road leading north near Mud Lake. The writers are in agreement with Chayes's findings that the flow marbles contain fragments of all rock *types* except those containing nepheline, but they disagree as to the age of the granite pebbles. The lime rocks of this type are cut by the visible granite. Some small rounded fragments of quartzite (or chert) were encountered, but no rock of that type was found in place within several miles of the locality.

In a thin section of lime rock from the railway cut the following relationships were observed: calcite, biotite, and microcline, in order of abundance and formation, are the chief minerals, magnetite and apatite being accessory. Patches of fibrous zeolite-like material, identical with the altered nepheline of other rocks, are partially replaced by albite. Biotite, associated with calcite, is embayed by the feldspars. The altered nepheline (?) is also associated with calcite. Microcline is the youngest mineral in the rock.

Similar relations have been observed in other sections, although nepheline or its alteration products are not present in every case.

MICACEOUS SCHISTS AND GNEISSES

Dark rocks rich in mica or, locally, in amphibole are abundant in the Bancroft area. They vary from relatively massive gneisses to strongly foliated schists; the massive varieties tend to be finer grained than the foliates. Many of them have been termed "shonkinite" by earlier workers.

Early in the study it was observed that certain bands of these paragneisses and schists contained nepheline. More careful examination brought to light the fact that basic rocks may actually change along the strike into gneisses, which carry a very appreciable amount of nepheline. This is particularly noticeable in the central band of basic rocks, cutting across Lots 23, 24, and 25 in Concession XIV and Lots 23, 24, 25, and 26 in Concession XIII; in Lots 27, 28, and 29 the rocks on strike with that band contain nepheline in increasing amounts. The change is gradual but is shown diagrammatically on the contact map on the east side of Lot 27, Concession XIII. The same gradation has been observed elsewhere not only along, but also across, the strike.

Many zones mapped as paragneiss,

[9] *Ibid.* In the present paper the question of large-scale intrusion of "carbonatite" is not treated in detail. The exposures, in the area, of "flow marble" are not considered so very different from similar exposures commonly found, where Grenville-type rocks exist (and where no alkaline rocks are found). The ability of calcite to "flow," to grout or seal fractured dikes or adjacent brittle sedimentary layers, and to be squeezed into certain structural openings, such as the nose of a fold, is well known.

adjacent to the granite and syenite, are granitic, obviously having suffered considerable attack by the intrusives. Indeed, in many places it is very difficult to place a contact between the basic paragneisses and the intrusives.

The minerals of the paragneisses and schists include the following:

"hastingsite"	scapolite
biotite	epidote
calcite	chlorite
albite	quartz
microcline	magnetite
perthite	garnet
pyroxene	sillimanite
muscovite	titanite

Garnet and sillimanite were not encountered in rocks of the Bancroft area, but they occur in schists not far to the south, in Lots 22 and 23, Concession X, Dungannon Township.

In the following sections some examples will be described. Since Adams and Barlow have presented very complete discussions of the mineral and textural relationships in most varieties of the rocks and since it was found that, in general, their conclusions were very acceptable, it does not appear necessary to reproduce them *in toto*. For further details the reader is therefore referred to the descriptions of Adams and Barlow.[10]

We are concerned chiefly with the foliates; the massive and finer-grained varieties are not abundant in the Bancroft area as defined and have not been observed to contain nepheline or its alteration products. Such rocks as the massive augite-hornblende-scapolite rock, occurring in the banded marble on the York River in Bancroft village, are referable to one of the groups of amphibolite set up by Adams and Barlow and probably represent impure limestones.

Dark micaceous rocks from the band along the East Road, Lot 24, Concession XIV, of Dungannon, contain green hornblende, "lepidomelane," sodic oligoclase, calcite, and apatite and titanite. The feldspars are somewhat altered to white mica, calcite, and epidote. The relation of calcite to the other minerals is rather uncertain; some appears to be original ("early"), other is secondary ("late"). Coarse calcite is associated with the ferromagnesian minerals and is apparently recrystallized original calcite. In one section it occurs in straight "laths," separated by the alternating development of mica foils.

A second gneiss from the same locality contains, in addition to the minerals mentioned above, microcline, some perthite, and scattered patches of fibrous material resembling highly altered nepheline in other rocks. Potash feldspars replace soda feldspars, and both embay hornblende.

Feldspathic gneiss from the Exolon Hill, Lot 24, Concession XIII, is composed of albite, biotite, microcline (perthite), and muscovite. The albite is clouded with small crystals of calcite, white mica, and epidote. The microcline is very fresh and is younger. The mica is partially converted to chlorite.

A light-colored gneiss from the Robertson Hill, Lot 26, Concession XIII, contains oligoclase, biotite, hornblende, iron oxides, and calcite. Veinlets of calcite cut the feldspar, mica, and altered hornblende (Fig. 5). Some large patches of almost fibrous calcite are continuous with the veinlets. Small crystals of fresh, secondary albite occur in altered areas; some of the alteration product appears to be fine-grained soda-zeolite (natrolite?), perhaps derived from nepheline.

FIELD RECOGNITION OF NEPHELINE

The pitted surface of the nepheline-bearing rocks is well known (Fig. 8). The

[10] Ftn. 4.

nephelineline, being more soluble than feldspar, tends to be removed, leaving ridges and humps of feldspar. The surface of the attacked nepheline is generally smooth and of a bluish-gray color. However, in the Bancroft area and, indeed, in all the areas examined, it was observed that in some cases the nepheline was altered to a white or creamy material. At first glance the rocks with white-weathering nepheline appear to be merely highly feldspathic types.

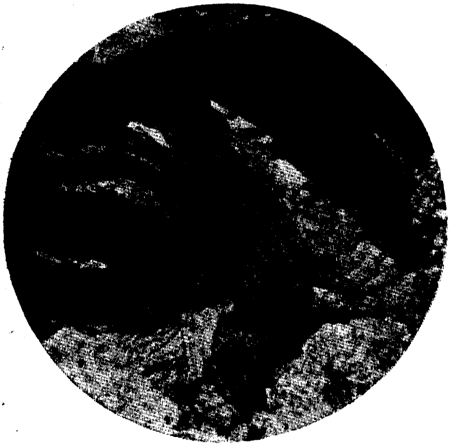

FIG. 5.—Crenulated biotite (in paragneiss) grouted by calcite. Robertson Hill, Lot 26, Concession XIII, Dungannon Township. Crossed nicols, ×45.

The bluish alteration product, which is rather readily removed, may be due to a superficial formation of sodalite, whereas the white or cream coating may perhaps be cancrinitic. A tendency was noted for the white surface to be present on the underside of cliffs and overhangs or in areas where vegetation is abundant. The bluish coating is more common on exposed outcrops.

NEPHELINE-POOR GNEISSES

The rocks of this group include those outwardly similar to the dark foliates of the nepheline-free group of rocks but containing nepheline and also certain light-colored gneisses of feldspathic nature, containing a small amount of nepheline. It is not uncommon to find lenses of nepheline-rich material, $\frac{1}{4}$–2 inches in width, in the gneisses; the lenses do not present intrusive relations but, on the contrary, appear to grade, albeit rapidly, into the surrounding rock.

The minerals and their relations in the nepheline-poor gneisses are essentially the same as in the normal paragneisses, with the exception that nepheline and its alteration products are more common, hornblende and biotite are less frequently observed, and microcline is more abundant. Some examples may be described.

On the south side of the Davis Hill, Lot 25, Concession XIII, occurs a belt of light-colored, interbanded, nepheline-rich and nepheline-poor gneisses, adjacent to and including some of the nepheline-free foliates. A section across a zone of the light-colored rocks shows that nepheline predominates in certain bands, whereas microcline predominates in others. Definitely two ages of plagioclase feldspar are present; coarse-grained albite or sodic oligoclase is the older and is replaced by finer-grained albite. Both feldspars replace biotite along cleavages and also replace calcite. One grain of albite was observed with the twinning lamellae parallel to the cleavage of a calcite grain. In a second instance cleavage in a grain of calcite conforms with cleavage in adjacent albite, and twinning in the same calcite conforms with cleavage in a second albite grain. However, some calcite replaces the earlier feldspar along cleavages; therefore, there is more than one age of calcite. This behavior of calcite is rather prevalent.

Nepheline-poor rock from the Robert-

son Hill contains hornblende, albite, calcite, and microcline, with cancrinite and a zeolite, alteration products of nepheline; the microcline replaces albite. At what stage the nepheline was altered is not obvious. Coarse calcite, up to $\frac{3}{4}$ inch in size of grains, is present, with an unusual arcuate twinning traversing straight cleavage, possibly the result of gliding; it exhibits cataclastic effects along fractures. Cancrinite forms fan-shaped patches around altered nepheline in the albite.

Gneisses from Robbins Hill have high-calcite, biotite, and hornblende contents; but, in some, feldspar is absent; cancrinite is abundant; and some scapolite has been observed.

NEPHELINE-RICH GNEISSES

Albite and nepheline form the bulk of the nepheline-rich rocks, the former generally being predominant. Biotite, magnetite, and calcite are present in nearly every slide examined but are generally minor in amount. Throughout the area the feldspar is chiefly albite,[11] from Ab_{90} to Ab_{97} as determined by extinction angles in the zone normal to (010) and by other methods. Universal-stage study proves the albite is generally in the neighborhood of Ab_{95}. It has undergone little alteration, even in those rocks in which the nepheline is completely altered. In many cases the relations between albite and nepheline are somewhat doubtful, but in many others albite is definitely younger. Also in some sections there are at least two ages of plagioclase, the older containing a few per cent more of the anorthite molecule and commonly being fractured. Generally the nepheline appears to have formed between the periods of formation of the two plagioclases and occurs in anhedral to subhedral crystals, embayed by the younger albite. Nepheline, as well as the younger albite, may be strongly fractured in some examples, but the indications are that the prominent fracturing occurred before the nepheline formed.

In the rocks with most nepheline, calcite is least apparent; but it increases as nepheline decreases and as ferromagnesians increase. Some calcite occurs as replacement remnants, whereas other examples are obviously secondary or late, perhaps recrystallized. In some rocks calcite grains are found almost entirely as inclusions in albite or are interstitial, rarely occurring as remnants in nepheline. Blebs of calcite may be oriented, in optical continuity, parallel to crystallographic directions in albite.[12] Rims and fans of cancrinite are common between nepheline and calcite. Calcite veinlets cut nepheline-apatite-calcite rock on Robertson Hill and in many other localities.

One particular section from Davis Hill is composed of rounded crystals of albite, nepheline, and biotite, separated from each other by calcite. Cores of calcite are also seen in cancrinite, against nepheline. The texture is identical with that found in recrystallized limestones containing silicate minerals.

Biotite, of the deeply pleochroic "lepidomelane" type, is common but rarely exceeds 10–15 per cent and is generally much less than that. Magnetite is typically to be found in intimate association with biotite, as is calcite. Some

[11] Oligoclase and even andesine are found in some types, for example, the "craigmontite" and "dungannonite" of Adams and Barlow (pp. 312 and 322, respectively, of ftn. 4).

[12] Chayes (Pl. 3, Fig. 2, facing p. 466, of ftn. 1) shows, in the left-hand picture especially, what might be taken as an excellent example of "caries," the result of the replacement of calcite by feldspar. Chayes interprets this as calcite replacing feldspar.

magnetite has been observed in skeletal crystal aggregates, of which the interstices are filled with finely crystalline albite. Hornblende ("hastingsite") is present, but rarely in the nepheline-rich rocks.

Apatite and zircon are minor but widespread, and eucolite or a similar rare-earth mineral has been observed. Occasionally, small apatite-calcite-feldspar bodies are observed and are probably related to the fissure fillings of similar mineralogy that have been adequately described by Adams and Barlow and others.

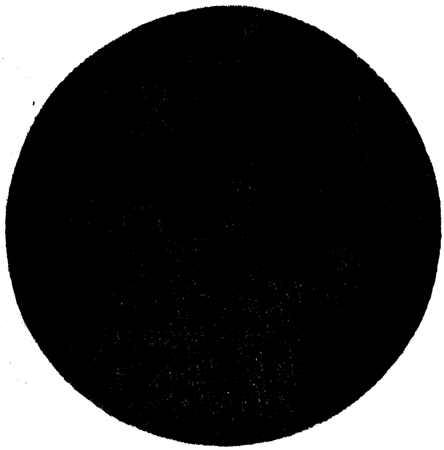

FIG. 6.—Zeolitic alteration of nepheline rock. Rosettes of secondary minerals growing along cleavages and cracks. Davis Hill. Crossed nicols, ×45.

Potash feldspar is also minor in quantity and is the latest-formed mineral, occurring interstitially to albite and nepheline and in some sections replacing those minerals. It is noticeably more abundant in certain bands, where it is frequently associated with the more intense alteration of the nepheline. It has been oberved also that microcline is more abundant adjacent to the pink syenitic dikes that are so common.

The nepheline is generally very fresh; but, adjacent to joints, faults, or dikes, it may be completely altered to fine-grained fibrous mats of cancrinite, sodalite, gieseckite (?), calcite, and a mineral that is apparently a soda-zeolite of the natrolite group. The commonly mixed nature of the alteration products does not lend itself to an accurate determination of the component phases. Sodalite has been observed as pseudomorphs after nepheline, but it also occurs in veinlets and separate grains of apparently primary nature.

The alteration products of nepheline were studied rather carefully. Several sections show positively that the alteration increases toward dikes (albitite in particular) and openings along which solutions might have operated. The alteration generally proceeds by the formation of fibrous, radiate-structured spherulites along cleavages, fractures, and grain contacts (Fig. 6). In one instance the alteration of nepheline adjacent to a joint was observed to have resulted in cancrinite near the joint but in zeolitic products farther away.

On the northwest flank of Robertson Hill occurs a lens or band of corundum-albite-nepheline rock. Corundum occurs in crystals reaching 1 inch or more in length and is separated from nepheline by albite.

NEPHELINE PEGMATITES

Two typical pegmatitic bodies are those occurring in the south parts of Lots 26 and 27, Concession XIII. They are composed essentially of nepheline and albite, crystals of the former reaching as much as 3 feet in length. Other minerals recognized are biotite; magnetite; sodalite; cancrinite; green, violet, and mauve "grieseckite"; orthoclase; and microcline. The bodies of rock are not

dikelike in form but are irregular in outline.

Elsewhere in the area, patches of pegmatitic rock are abundant. On the west flank of Cancrinite Hill occurs a zone of striking yellow cancrinite and blue-to-purple sodalite, which is simply an alteration of the nepheline gneisses. On Princess Hill, Lot 25, Concession XIV, there is an irregular length of pegmatitic albite, microcline, and sodalite, at one time worked for ornamental stone. The occurrence is characterized by numerous vugs. The feldspars tend to be euhedral, in a groundmass of streaked sodalite. No intrusive relations were observed; on the contrary, the body seems to be a replacement.

Throughout the area large crystals of nepheline may be encountered in the fine- to medium-grained nepheline gneisses. An outstanding example was noted on a large angular piece of float in the valley to the south of Davis Hill. A shear zone crosses the foliation of the nepheline gneiss roughly at right angles. Two crystals of nepheline, about 8 inches in longest dimension and euhedral in form, have been developed across the crack and also across several albite-rich bands. Remnants of the albite-rich bands remain in the nepheline crystals and show distortion. This seems to be a clear case of recrystallization of the nepheline, with concomitant replacement of the host-rock.

Another feature of such examples is the common association of large magnetite crystals with the coarsely crystallized nepheline. In some of the coarser gneisses, vugs were observed, lined with euhedral magnetite crystals reaching $\frac{1}{2}$ inch in diameter. One large body of magnetite is known; and several dikelike bodies, the largest about 15 inches wide, were encountered. A paragenetical relation between recrystallized ("regenerated") nepheline and late magnetite is indicated.

Another point worthy of observation is the abundance throughout the region as a whole of pegmatitic zones, streaks, and bodies containing coarse calcite with the silicates. The well-known occurrences of calcite fillings or replacements in joints in nepheline rock, lined with coarse nepheline, albite, mica, and apatite, are examples. Several pegmatites locally have extremely coarse-grained calcite matrices, and others contain lenses of more or less pure calcite. There is, then, an obvious conclusion, that the pegmatites were closely connected with the formation of calcite in large amounts.

ALBITITE DIKES

Under this heading are classed those bodies of rock, large and small, that are composed almost entirely of albite and that are apparently cross-cutting.

Study of the weathered surface of many exposures of the nepheline rocks yields an interesting fact: the rock is *not* invariably an intimate granular mixture of albite and nepheline; instead, those minerals tend to be segregated into bands. A "stringer" of albite, perhaps only $\frac{1}{8}$ inch wide, may be perfectly continuous for several feet, composed of adjoining crystals of albite that at first glance may appear to be evenly dispersed throughout the nepheline (Fig. 7). Wider bands are continuous over still greater distances. It was observed in the field that the contacts of some of the albite "dikes" with nepheline gneisses are gradational. Some crystals or crystal aggregates of albite are actually shared by the gneiss and the "dike," and some attenuated streaks of albite in the nepheline rock may be seen to pass uninterruptedly into the coarser albite of the

"dike" (Figs. 7 and 8). This immediately suggests that the albite might have been formed, at least in part, by simple silication of nepheline, which spread laterally from joints and fractures—a process that

FIG. 7.—Albite stringers in nepheline-rich gneiss. Lot 27, Concession XIII, Dungannon Township.

appears likely by virtue of the fact that the visible granitic rocks are postnepheline in age.

The albitite rocks are most conspicuous, if not actually most abundant, in the Bronson Hill exposures. They occur throughout the area, however, and are evidently most abundant adjacent to granitic or syenitic contacts.

Under the microscope, Bronson Hill albitite presents the following relationships: albitite of high purity comprises well over 95 per cent of the rock; microcline is perhaps the next most abundant mineral. Calcite, magnetite, biotite, apatite, zircon, white micas, and sodalite are present. Microcline is younger than the bulk of the albitite and is associated with finer-grained albitite and, quite frequently, with skeletal magnetite aggregates. Calcite occurs as rounded replacement remnants. The presence of sodalite suggests a genetic connection with the nepheline rocks; it occurs as small subhedral grains interstitial to the albite, with no indication that it represents original nepheline. However, small and irregular patches of material very similar to the altered nepheline of other rocks are present.

Chayes[13] has suggested that some albite-rich pegmatites, dikes, and veinlets represent "either a syenitic residue which has somehow escaped desilication, or late acid pegmatite which has been 'albitized' by the addition of solid alkalies and alumina"; or that the albitite has been formed by reaction of foyaitic liquid and solid syenite. The writers conclude from examination that the veinlets in the Vardy Quarry (mentioned by Chayes) and elsewhere are the result of siliceous mineralizers acting on nepheline, which is the opposite effect to that postulated by Chayes. However, he does mention the possibility that some "veinlets of syenite . . . . may be the product

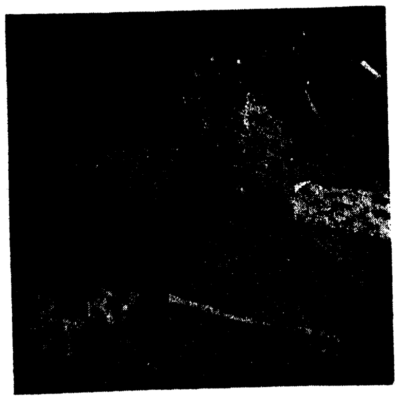

FIG. 8.—Relations between nepheline-rich gneiss, albitite (with nepheline), and nepheline pegmatite. Bronson Hill.

of reaction between a nepheline-rich rock and very small quantities of highly silicic liquid."[14] This would seem to be a more correct interpretation.

[13] *Ibid.*, p. 488.

[14] *Ibid.*, p. 496.

GRANITE, SYENITE, ETC.

The obviously intrusive rocks, then, are apparently limited to the granite, syenite, and related types. These latter include quartz syenite, biotite and hornblende syenite, granite and syenite pegmatite, and feldspar-rich dikes, which are pink and appear in decided contrast to the white "albitite dikes." Granite is commonly gradational into syenitic border facies; in other places the granite is gradational into paragneisses, and it is entirely arbitrary with which group of rocks the granitization product is to be mapped. A good deal of rock included with the granite is gneissic and contains obvious remnants of paragneiss (sometimes containing nepheline, as in the east end, Hastings Road, Lot 60, and in the north half of Lot 28, Concession XIII, just west of Mud Lake).

In several localities quartz-bearing granite is in immediate or very close contact with limestone or nepheline-bearing rocks. Granite with abundant quartz occurs in the east half of Hastings Road, Lot 59; to the north of that, nearer the East Road; and just west of Mud Lake. The intrusive tongues north of Princess Quarry and much of the rock along the East Road in Lot 23, Concessions XIII and XIV, contain quartz. Quartz pegmatite is found on the flank of Robertson Hill, in nepheline-poor and nepheline-free gneisses. Quartz-aplite cuts nepheline rock on Davis Hill. Only a few of the feldspar-rich dikes and sills are of mappable dimensions, and some of those shown are approximated.

Much of the syenitic phase is blotchy, with inclusions of altered paragneisses. Under the microscope the rock is seen to be composed essentially of microcline and perthites; some microcline and albite are younger than the perthite.

The following minerals have been recognized in the granite and related rocks:

perthites	apatite
microcline	titanite
orthoclase	zircon
albite	pyrite
quartz	white mica
biotite	epidote
hornblende	chlorite
augite	serpentine
magnetite	

The presence of the iron-rich "lepidomelane" and of "hastingsite" in the intrusives has previously been used as a criterion of consanguinity with the paragneisses and nepheline rocks which contain the same minerals.

No calcite has been observed in normal granite, whereas it is common in the syenites. Yet the granite can be seen to grade into syenite where overburden does not mask the relations.

STRUCTURE

The delineation of a recognizable structure, which includes the nepheline-bearing rocks as important units, has been as helpful as any other phase of the study in pointing to the origin of the nepheline rocks.

The rocks of the area are everywhere more or less gneissic, the nepheline rocks lying in definite bands intercalated between gneisses, whose sedimentary origin is at once apparent (Figs. 9, 11, and 12). The strike of the rocks is prevailingly northeast; dips are mainly southward and vary from almost vertical to as low as 10°.

Even the granite, especially adjacent to the gneisses, has a pronounced foliation that may be primary ("flow") structure or inherited through granitization. Many intrusive bodies show concordant relations, as, for example, the main north and south contacts of the granite and syenite with the paragneisses and the

lens-shaped smaller bodies. Elsewhere contacts are obviously of intrusive, discordant character. The bodies of paragneisses west and north of Mud Lake appear to be large inclusions or remnants caught up in the granite.

Drag folds are common, recognizable chiefly in the micaceous parasediments and the crystalline limestones but also found in nepheline rocks (Fig. 10). The limestone in east Lot 61, Faraday Township, is dragged in such fashion as to suggest an anticline to the south, plunging to the west. However, drag folds located elsewhere indicate a syncline plunging to the east and, therefore, that drag folding may indicate only local effects in the readily folded limestones.

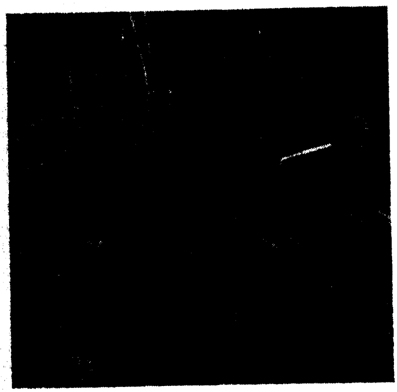

FIG. 9.—Well-banded paragneisses, south of Davis Hill, Lot 25, Concession XIII, Dungannon Township.

There are two main bands of nepheline-bearing rocks which unite in Lots 29 and 30, Concession XIII, and continue as one band to the west (see Fig. 4). In east Lot 59, Dungannon Township, as nearly as can be ascertained from surface exposures, granite has isolated the westward extension. Lying between the two bands, from the east end of the mapped area to their junction, is a belt of rocks, which in the eastern section is composed chiefly of nepheline-free paragneisses with a few narrow nepheline-bearing bands. This facies apparently grades into gneisses carrying nepheline, which increases in quantity westward along the strike. A similar gradation is to be found to the south of the southern band of nepheline-rich rocks in Lots 26 and 27, Concession XIII. Still farther south occurs a band of paragneisses with minor nepheline (Lots 23, 24, 25, and 26, Concession XIII). A comparable zone is present north of the East Road in Lots 26 and 27, Concession XIV, but is not shown on the map. Small bodies of nepheline-poor rock occur here and there throughout the nepheline-rich and nepheline-free rocks.

The explanation offered here of this distribution is that the nepheline gneisses and other paragneisses are parts of an overturned syncline plunging to the northeast. The succession of the gneisses in the area covered by the map is roughly as shown in the accompanying tabulation.

Inner belt......	Some limestone, calcareous schists and paragneisses, occasional nepheline
	Nepheline-poor paragneisses
Middle belt.....	Nepheline-rich paragneisses
Outer belt......	Nepheline-free and nepheline-poor paragneisses
	Crystalline limestone, etc.

The limestone in center Lot 29, Concession XIII, is explained as a synclinal remnant, remaining because of the local topography. The limestone along Concession XIII in Lots 26 and 27 is believed to be on the nose of an anticline to the south, the outline of that nose being indicated by the concordant nepheline pegmatite in the same area. Limestone is suggested as a continuous band around the west end of the syncline toward Ban-

croft. The long, dissected body of limestone north of the East Road in Lots 28 and 29, Concession XIII, is a remnant of the same band. The two bodies were separated by the granite, which has invaded the nepheline-rock belt, and apparently some limestone has flowed, as suggested by Chayes, but not after emplacement of that granite. Impure limestones interbedded with more or less calcareous paragneisses were encountered in a drill hole on the west side of Cooney Hill, between nepheline rock and granite.

The straight gorge of the creek below Mud Lake may indicate a fault. If so, it would aid in explaining the appearance of a lens of nepheline-poor and nepheline-free gneisses (mapped as "nepheline-free") just below the lake. A fault may also be present between Davis and Robertson Hills. Minor faulting is present throughout the area (Figs. 11 and 12).

The sinuous outline of the main belt, especially north of the East Road in Concession XIII, is due in large part to topography (Fig. 14). However, there has certainly been folding and faulting later than that which formed the major structure.

The strikes of the nepheline gneisses, on Davis, Cancrinite, Cooney, Princess, and North hills, trace out subsidiary drag folds on the arms of the major fold (Fig. 15). Owing to the overturned nature of the fold, the axial dips of the drags in the two arms are similar.

ANALYTICAL DATA

Adams and Barlow[15] presented several analyses of what they considered type nepheline rocks. On the basis of the C.I.P.W. classification, they set up several new species of nepheline rocks. Among the old and new types recognized were essexite, laurdalite, nepheline syenite (vulturose), monmouthite, miaskite, syenite (kallerudose), craigmonitite, raglanite, and dungannonite. It is contended that many additional and different analyses could have been obtained, because, in those finely foliated gneisses, contiguous bands have different compositions both chemically and mineralogically. Adams and Barlow themselves remarked on the strikingly rapid variation of the rocks, which is difficult to explain if the nepheline rocks are considered to be intrusive.

FIG. 10.—Drag-folding in paragneisses on south side of Cancrinite Hill, Lot 25, Concession XIII.

During the course of the present investigation many analyses were made; although most of them were only partial, there is sufficient variety that still other rangs and subrangs of the C.I.P.W. classification could be set up. However, field evidence negates the value of applying those recasting methods to the nepheline rocks. Our analyses indicate that the amounts of the various oxides in the rocks cover a wide range. For instance, silica varies from 35 to 60 per cent in rocks of the area; alumina varies from 17 to 34 per cent. Samples from all parts of the area have been analyzed;

[15] Ftn. 4.

study of the results has shown that, in the Bancroft area, the total of the R_2O_3 constituents is commonly around 30 per cent (see Tables 3 and 5). If Al_2O_3 comprises 25 per cent, Fe_2O_3 and TiO_2 (and MnO, P_2O_5, ZrO_2, etc.) comprise about 5 per cent; if Al_2O_3 is 20 per cent, the other oxides are about 10 per cent; and if Al_2O_3 is 30 per cent, the other oxides are low, 2 or 3 per cent.

The rough constancy of the sum-R_2O_3, that is, the indicated reciprocal relation between Al_2O_3 and Fe_2O_3, and the similar relation between CaO and alkalis (as comprising the larger part of the undetermined portion in the analyses) are believed to have some bearing on the origin of the nepheline rocks.

The analyses have also shown that certain zones within the main nepheline bands contain more nepheline than others. These zones have been outlined as drag folds and appear as S-shaped bodies. Their disposition agrees with that

FIG. 11.—Fault in mixed nepheline-poor and nepheline-free paragneisses, Lot 27, Concession XIII.

FIG. 12.—Details of downthrow side of fault shown in Figure 11. A 1-foot syenite pegmatite seals the fault.

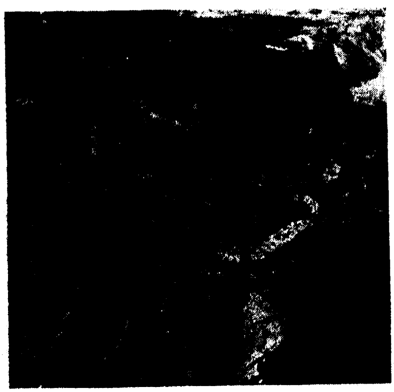

FIG. 13.—Crumpling of paragneisses (some with nepheline) and limestone. Egan Chute, York River.

FIG. 14.—View looking westward from Davis Hill. Cooney Hill in right center distance, Mountney Hill in left distance.

of the apparent drag folds on the limbs of what has been assumed to be the major syncline. It then appears that the distribution of nepheline-rich zones is determined by the structure, and therefore it is logical to conclude that the nepheline was formed after the major folding. The general fracturing in the earlier feldspar of the gneisses and the lack of that fracturing in most cases in the nepheline agree with this conclusion.

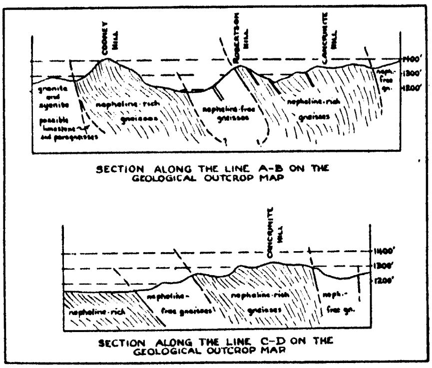

FIG. 15.—Cross-sections as indicated in Figure 3, showing secondary folding on limbs of the major overturned fold.

Analytical results also suggest that, in some places, rocks at the surface are richer in alumina than those occurring at depth. This probably indicates that calcite has been removed at the surface by weathering, yielding a relative increase in the other oxides. Some analyses are given in Table 2.

A typical drill-core log is given in Table 4, showing the variation recognized. In Table 5 are presented the analytical data on the samples represented by the log.

OTHER AREAS OF NEPHELINE ROCKS

YORK RIVER AREA

A relatively small amount of work was done by the writers in the York River area (the band of paragneisses, crystalline limestones, and nepheline-bearing gneisses along the east side of the York River, north of the East Road, some 6 miles east of Bancroft). Some important information was, however, derived from the study.

TABLE 2

ANALYSES OF NEPHELINE ROCKS

Oxide	I*	II	III	IV	V	VI
SiO_2	47.2	48.2	41.8	49.7	47.4	54.6
TiO_2	0.1	n.d.†	0.3	0.1	0.2	0.2
Al_2O_3	28.1	26.3	29.5	22.4	27.4	21.6
Fe_2O_3	3.7	4.1	5.2	6.8	3.1	1.9
MnO	0.02	n.d.	0.02	n.d.	n.d.	n.d.
CaO	1.7	2.1	5.1	1.3	1.8	3.6
MgO	0.5	n.d.	1.3	n.d.	n.d.	n.d
L.O.I.	1.8	2.8	1.3	1.7	1.6	3.6
R_2O_3	31.9	30.4	35.0	29.3	30.7	23.7

* I—Surface sample, 11 feet width, Mountney Hill, Lot 29, Concession XIII, Dungannon Township. Analyst, W. K. Gummer.
II—Surface sample, 360 feet width, Princess Hill, Lot 25, Concession XIV, Dungannon Township. Analyst, E. M. Weaver.
III—Surface sample, 13 feet width, north ½, Lot 8, Concession XIV, Dungannon Township. Analyst, W. K. Gummer.
IV—Core sample, 71.5 feet length, Davis Hill. Analyst, E. M. Weaver.
V—Core sample, 13.5 feet length, Bronson Hill, Lot 60, Hastings Road. Lots, Dungannon Township. Analyst, E. M. Weaver.
VI—Core sample, 13.5 feet length, Bronson Hill. Analyst, E. M. Weaver. (Contains albitite dikes and altered [cancrinitic] nepheline.)

† n.d. = not determined.

TABLE 3

AVERAGE R_2O_3 FIGURES, BANCROFT AREA

Sample Description	Percentage R_2O_3
35 core samples, 1330.8 feet, nepheline-bearing rocks	29.4
66 core samples, 2029.0 feet, nepheline-bearing rocks	29.5
8 core samples, nepheline-free gneisses, syenite, etc.	27.0

The nepheline rocks are generally quite different from those of the Bancroft area. They appear to lie in more definite and less contorted bands, and the parasedimentary rocks associated with them are perhaps somewhat more abundant.

Most of the rocks contain far more hornblende and biotite, less feldspar, and generally less nepheline; accessory minerals include red garnet, corundum, zircon, and eucolite, which are rare or lacking in Bancroft area rocks but which in York River rocks may locally become important constituents. Microcline is but rarely to be found, but scapolite is more common than in the Bancroft area.

TABLE 4

SAMPLE DRILL-CORE LOG

Hole 7 — Exolon Hill — Bearing N.72° W. ast. — Lot 24 Concession XIII Dungannon Township — Length, 258 feet — Angle 45°.)

Footage	Description	Sample	Width
0.0– 7.0.........	Casing		
7.0– 45.0.........	Medium- to fine-grained nepheline rock; small quantity of dark minerals, mainly hornblende; 0.5 feet biotite-calcite band at 9.5 feet; strong "gieseckite" alteration over last 10 feet		
	7.0–25.0, as above	40	18.0
	25.0–45.0, as above	41	20.0
45.0– 71.7.........	Coarser nepheline rock, with larger amount of biotite and hornblende; alteration to "gieseckite" common; apparently higher feldspar		
	45.0–71.7, as above	42	26 7
71.7–100.0.........	Finer-grained nepheline rock with lower ferromagnesian content; considerable pink and green alteration; feldspar content appreciable; 0.8 foot calcite-sodalite at 82.0		
	71.7–100.0, as above	43	28.3
100.0–105.0.........	Much biotite; hornblende and feldspar; small amount of nepheline		
	100.0–105.0, as above	44	5.0
105.0–111.5.........	Nepheline rock similar to 71.7–100.0		
	105.0–111.5, as above	45	6.5
111.5–141.0.........	Very patchy nepheline rock, locally rich in dark minerals; much "gieseckite" and natrolite alteration; pink syenite dikes 121–23, and 129–32; several small syenitic sections		
	111.5–141.5, as above	46	29.5
141.0–258.0.........	Syenitic rocks, little or no nepheline; calcite-biotite-cancrinite, 214.1–214.9; sampled		
	141.0–151.0, as above	47	10.0

TABLE 5

ANALYSES OF SAMPLES 40–47 INCLUSIVE

Sample	Percentage							
	L.O.I.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	CaO	Total Determined	R_2O_3
40.............	3.7	48.5	0.28	24.3	5.2	5.9	87.9	29.8
41.............	3.3	46.7	0.30	26.1	5.4	2.7	84.5	31.5
42.............	6.4	44.9	0.32	19.2	9.0	7.6	87.4	28.5
43.............	3.6	49.3	0.28	24.0	5.3	3.3	85.8	29.6
44.............	2.4	46.9	1.54	17.3	11.5	7.5	87.1	30.3
45.............	4.3	50.6	0.26	25.5	4.5	2.6	87.8	30.3
46.............	2.7	51.8	0.92	17.1	8.9	3.7	85.1	26.9
47.............	1.4	54.3	0.50	19.9	7.8	3.0	86.9	28.2

Green hornblende may form as much as 80 per cent of some of these rocks; in others biotite of the deeply pleochroic type takes its place in part. Garnet occurs both as separate crystals and as rims (reaction?) around hornblende crystals or crystal clusters. No rocks were observed to which Chayes's term "migmatite" could be applied. He states that "the garnet-hornblende-nepheline rocks near Egan Chute . . . . are produced by injections of nepheline pegmatites into garnet-amphibolite."[16] The mixture is actually very intimate, the result of a soaking rather than an injection. It was in this area that F. F. Osborne was led to believe that replacement had played a part in the development of the nepheline rocks.[17]

The contrast between the mineralogy of the York River rocks and the Bancroft area rocks is further discussed at a later point. In the York River area the sum-R_2O_3 again tends to be similar in various rock types, although it is considerably higher than 30 per cent in the iron-rich varieties. Alumina determinations vary from 8 to 31 per cent, and iron oxide averages around 10 per cent. Alkalis (6–12 per cent) and silica (30–45 per cent) are lower than in the Bancroft rocks; lime is higher, reaching 19 per cent in certain rocks.

It has already been stated that Adams and Barlow considered the granite occurring west of Egan Chute to be younger than the nepheline rocks.[18] In further support of that contention is the existence of quartz-bearing pegmatites that cut the nepheline gneisses. For example, a few hundred feet north of the East Road, a quartz-feldspar pegmatite cuts across interbedded nepheline gneiss and crystalline limestone. Where the dike traverses the nepheline rock, the amount of quartz is restricted and is confined to the center of the dike.

In the first small quarry encountered on the road paralleling the York River, nepheline pegmatite underlies limestone and has apparently replaced a portion of that rock. Near by the limestone is much coarsened in grain size and contains abundant red garnet, black spinel, and white cancrinite. Farther north, nepheline pegmatite apparently cuts across the crest of a drag fold in nepheline gneiss. Other pegmatites observed have rather irregular and indefinite contacts.

THE TORY HILL–GOODERHAM AREA

The rocks of this area have points in common with rocks of both the Bancroft and the York River areas. All are gneissic and are associated with similar parasedimentary rocks. Locally, limestone contains pebbles and possibly represents the limestone-conglomerates occurring some miles to the south and southeast.

On Lot 34, Concession IV, Glamorgan Township, four features are marked: (1) Typical biotite schist and hornblende gneiss locally contain nepheline; Satterly[19] has recently corroborated this. (2) Nepheline pegmatite has been traced half a mile or more, following the drag-folded configuration of the metamorphosed sediments. (3) The contact between the coarse pegmatite and the crystalline limestone, exposed in a small quarry, is entirely gradational. Away from the pegmatite, silicates, including nepheline and albite, are present in the limestone; and in the pegmatite, decreasing in size and abundance away

[16] Chayes, p. 486 of ftn. 1.

[17] "The Nepheline-Gneiss Complex near Egan Chute, Dungannon Township, etc.," *Amer. Jour. Sci.*, Vol. XX (5th ser., 1930), p. 33.

[18] Cf. ftn. 4.

[19] P. 17 of ftn. 7.

from the limestone, are remnants of that rock. Replacement is the only satisfactory explanation to account for the bulk, at least, of the pegmatite. (4) One 8-inch albite-nepheline band in "nepheline-amphibolite" (gneiss) appears to be intrusive; the nepheline is concentrated along the medial line of the dike.

The type "monmouthite" area (Lots 9, 10, and 11, Concessions VII and VIII, Monmouth Township) includes rocks in which the nepheline content varies from 10 to 95 per cent of the whole. The nepheline rock also contains green hornblende, biotite, albite, calcite, graphite, cancrinite, and zeolite-like alteration products of nepheline. The northern contact in one place is seemingly gradational into crystalline limestone containing much hornblende, as well as graphite, tourmaline, titanite, and chondrodite. Some limestone south of the Gooderham–Tory Hill road, in the same area, contains scattered crystals of nepheline.

THE BLUE MOUNTAIN AREA

The Blue Mountain area has been described by Keith,[20] who carried out a great deal of petrographic study and concluded that the nepheline rock is intrusive. He also decided that the granitic rocks are younger than the "litchfieldite," supporting his field evidence with age determinations by helium ratio.

The evidence gathered in other areas prompted some examination of the Blue Mountain exposures. Keith has stated that there is little evidence of deformation of the intrusive; however, it has been observed that both vague streaks and more prominent schlieren in the nepheline rock are strongly contorted. Indeed, the general delineation of the boundaries of the alkaline rock suggests tight folding. The Blue Mountain rock is, however, much more massive than rocks of the other areas.

In the rocks examined toward the southern end of the body in the present quarry, corundum is present but was not observed in actual contact with nepheline. It is found only in certain horizons, in irregular patches of albite with spinel (hercynite?) in the nepheline rock reaching several feet in length. Drill cores were studied and indicated that a correlation of horizons was possible, which is tantamount to saying that a pronounced stratification or foliation exists.

Chemically, the Blue Mountain rocks show less variation and are richer in silica and lower in lime than are the Bancroft rocks. Alumina and alkalis are about the same, although the ratio $K_2O:Na_2O$ is greater in Blue Mountain rocks, in which potash feldspar is an important constituent.

THEORETICAL CONSIDERATIONS

GENERAL DISCUSSION

The study of alkaline rocks, not only of the area under consideration but also of many other areas, has given rise to a voluminous literature. Space does not permit a thorough review of that literature, nor is it deemed requisite.

Among the major theories of the formation of alkaline rocks in general, the following may be listed: (1) desilication of granitic magma by limestone,[21,22] (2) fractional crystallization,[23] (3) volatile

[20] Ftn. 5.

[21] R. A. Daly, *Igneous Rocks and the Depths of the Earth* (New York: McGraw-Hill Book Co., Inc., 1933).

[22] S. J. Shand, "Limestone and the Origin of Feldspathoidal Rocks," *Geol. Mag.*, Vol. LXVII (1930), pp. 415–26.

[23] N. L. Bowen, *The Evolution of the Igneous Rocks* (Princeton, N.J.: Princeton University Press, 1928).

transfer and concentration,[24,25] and (4) combinations and variations of the first three.

The alkaline rocks of the Haliburton-Bancroft region were early considered related to the granites and the limestones. Adams and Barlow[26] stated that the nepheline syenite and its associated alkali syenites represent marginal differentiation of the granite. On the basis of their study they distinguished four rock groups, believed to be consanguineous differentiates of one highly alkaline and aluminous magma.

Later work has consistently pointed to the connection betweeen the limestone and the nepheline rocks, although just as consistently assuming at least the bulk of the latter to be intrusive.

Osborne [27] concluded that some rocks in the York River area are replacements rather than intrusives. Keith[28] believed the Blue Mountain nepheline rock to be intrusive, but he realized that the granite there and elsewhere in the nepheline-rock zones is younger. H. W. Fairbairn[29] examined a specimen of the "litchfieldite" and concluded that it possesses a fabric that is probably due to magmatic flow and crystallizing pressure.

Recently Chayes has supported the limestone-syntexis hypothesis as developed by Daly, Shand, and others. He reports the development of syenite as a marginal facies of the granite, and shonkinitic hybrids as a result of the "intimate mixing of amphibolite with syenitic liquid."[30] He rejects Keith's age determination of the granitic rocks, chiefly, it appears, on the ground that the helium-ratio determinations used were of doubtful accuracy, although Keith presented field evidence that the "syenodiorite" is younger than the "litchfieldite." As a result of his decision that the granites of the Bancroft area are not postnepheline in age, Chayes has some difficulty in reconciling the syntexis hypothesis with the abundance of "late acid pegmatites" and concludes that they exist "in spite of assimilation."[31]

The present evidence requires a further change in viewpoint. We now know that the nepheline rocks do not occur entirely in limestone or between limestone and granitic rocks; on the contrary, they occur in bands in a very heterogeneous series of altered sedimentary rocks and were invaded by the visible granite. At least some of the rocks hitherto termed "shonkinite" are shown to be nothing more than facies of the metamorphosed sediments; others appear to be hybrids between granite and sediments. Certainly, some syenite has been developed at the borders of the granite, but it may be found against several types of paragneiss, including those with nepheline.

The following features may be reviewed:

[24] C. H. Smyth, Jr., "The Genesis of Alkaline Rocks," *Proc. Amer. Phil. Soc.*, Vol. LXVI (1937), pp. 535–80.

[25] J. L. Gillson, "On the Origin of Alkaline Rocks," *Jour. Geol.*, Vol. XXXVI (1928), pp. 471–74.

[26] P. 228 of ftn. 4.

[27] Ftn. 17.

[28] Ftn. 5.

[29] "Petrofabric Relations of Nepheline and Albite in Litchfieldite from Blue Mountain, Ontario," *Amer. Min.*, Vol. XXVI (1941), pp. 316–20. As a matter of fact, almost any rock, even unconsolidated material, may exhibit a fabric, particularly those rocks affected by metamorphism in any of its manifestations. Evidence of a fabric in Bancroft rock was obtained from thin-section study; for instance, the albite grains in one slide yielded a large number of near-centered optic-axis figures. The albite and biotite show greater tendency toward preferred orientation than does nepheline.

[30] P. 495 of ftn. 1.

[31] *Ibid.*, p. 504.

1. The nepheline rocks are generally banded in character.
2. The nepheline rocks are conformable in attitude to the surrounding gneisses and schists, and they exhibit similar structures.
3. There is a gradation from nepheline-free normal paragneisses and schists, through nepheline-poor rocks into nepheline-rich rocks.
4. Calcite is present in widely varying amounts in all the rocks except the typical quartz-bearing granite; in the paragneisses and nepheline rocks, it is least in those richest in nepheline and increases with increasing biotite.
5. In general, the silicates appear to have been formed at the expense of calcite; there is also considerable younger calcite.
6. Nepheline is commonly unfractured, and zones of high-grade (alumina-rich) nepheline rock appear to have been localized by previously developed structural features.
7. There is no field evidence at erosion levels of the production of nepheline-syenite magma through reaction between solid limestone and granite magma.
8. The visible examples of intrusive, cross-cutting nepheline rocks are very rare and are limited to certain pegmatitic bodies.
9. The granite and syenite are definitely younger and intrusive into the nepheline rocks; reaction between them and limestone appears to have been limited to the production of some more basic facies of the intrusives and of pyroxenitic and amphibolitic contact rocks of the limestones.

Proponents of the limestone-syntexis hypothesis, which, as applied in the Bancroft area, proposes the development of nepheline syenite and more specialized *magmas* through the assimilation of solid limestone by granite magma, must account for those features. There are some obvious difficulties.

THE NEPHELINIZATION HYPOTHESIS

The theory is here advanced that the nepheline rocks are the result of the replacement of certain horizons of the sedimentary series by materials emanating from a source as yet unknown, at some time after the major structural features had been formed. This process, which may be termed *nephelinization*, apparently took place in large part through a reciprocal reaction involving soda and lime. That is indicated, of course, by the presence of some rocks relatively rich in calcite and poor in nepheline and albite and of others poor in calcite and rich in the alkaline silicates and by the presence in some rocks of two (or more) ages of plagioclase feldspar, the younger being richer in soda.

The term "nephelinization" is here used to specify the end-result and does not imply that nepheline was, or was not, added as such.

This hypothesis was first advanced in abstract form.[32] Satterly[33] and Thomson[34] have reached much the same conclusions from somewhat less detailed study. Replacement will explain all the major difficulties, including the continuity of the nepheline-bearing horizons on a large scale, the structure, and the variation of mineral constituents.

If limestone syntexis, with the usual concept of the production of actual nepheline-syenite magma, occurred at all, it must have done so at depth, beyond the zone of observation; this process would have been followed by upward movement of the newly formed feldspathoidal liquid, intrusion into various sediments, solidification, and, finally, intrusion of normal granitic magma and its satellitic dikes.

In contrast, the nephelinization hypothesis calls for the addition of material in liquid form (or volatile, or both) to solid strata *in situ*, without the actual

[32] W. K. Gummer and S. V. Burr, "The Nephelinized Paragneisses of the Bancroft Region, Ontario," *Science*, Vol. XCVII, No. 2517 (1943), pp. 286–87.

[33] P. 17 of ftn. 7.

[34] P. 14 of ftn. 2.

formation of a separate feldspathoidal magma or magmas.[35]

The concept of "granitization," whereby existing rocks become modified, through the action of mineralizers from granite magma, to a state in which they contain the minerals of a granite and in extreme cases resemble a granite not only mineralogically but also texturally, enjoys a favorable reception. The process of "albitization" is also fairly widely accepted. The process of "nephelinization," the term here indicating what is formed rather than what is added, is pictured as operating in the same general manner; but in this case some feature—whether physical or chemical—of either the mineralizers or the sediments, led to the formation of the undersilicated compound, nepheline, along with albite. Later action by the younger granite[36] produced still more albite in the nepheline rocks, probably by the process known as "silication" in the sense that silica was added to the rocks.

CHARACTER OF THE NEPHELINIZATION PROCESS

Nature of the rocks prior to nephelinization.—Conceivably, several distinct types of rock might undergo attack by igneous emanations to yield undersilicated compounds rich in soda and alumina. The addition of soda and silica to alumina-rich minerals, the addition of soda and alumina to feldspathic materials, the addition of soda to aluminum silicates—such reactions may be guessed at, but their substantiation is another matter. Equations might be written to illustrate the various conceivable reactions. The following are presented as possible rock types capable of undergoing alteration to nepheline-bearing rocks:

1. *Saline deposits.*—None are known in this or other areas of Grenville-type rocks.
2. *Arkoses.*—None are known in this area.
3. *Lateritic deposits.*—None are known, but the suggestion is an intriguing one, since an ancient weathering product of lateritic nature would be rich in both alumina and iron.
4. *Shales or slates, or such rocks as sillimanite schists.*—Quartz-sillimanite schist is known in the region, but in minor quantity. Although occurring not far from nepheline rocks, i shows no signs of the development of nepheline.
5. *Impure lime rocks.*—These contain alumina, silica, and iron in addition to calcium carbonate.

In the Bancroft region there is evidence of the existence of only types 4 and 5, and the rocks of type 4 are quantitatively unimportant; nor is there any indication in nepheline rocks that they were derived from aluminum-silicate rocks. On the other hand, mica (amphibole)-feldspar-calcite rocks, undoubtedly of sedimentary origin, are common, and many contain nepheline or minerals which are logically classed as alteration products of nepheline. It is therefore indicated that the "nephelinized" rocks were originally impure calcareous sediments. How much of the mineralogy of the paragneisses is the result of prenepheline metamorphism is not known.

The possibility that the nepheline rocks were formed from the purer varieties of the crystalline limestones has naturally been considered but has been discarded, (1) since nepheline is far more abundant in the impure calcareous rocks,

[35] T. T. Quirke has suggested a rather similar origin ("pneumatolytic replacement") for the nepheline rocks of the French River area, Ontario (personal communication).

[36] At this point we can mention the hitherto all-important areal association of the granite with the nepheline rocks. The apparently zonal relationships between the two rock types have been considered by Chayes (p. 498 of ftn. 1) and others as unlikely if the granite is the younger rock. However, the emplacement of the granite was probably in large part controlled by the same structural features that localized nephelinization.

(2) because in those rocks it is possible to recognize several degrees of nephelinization, and (3) because, although relatively pure limestones are to be found containing nepheline and other obviously introduced minerals, the source of the nepheline is generally indicated to be connected with a pegmatitic body. The rocks that are here considered as representing impure calcareous sediments may contain a trace, a medium amount, or a great deal of nepheline; whereas relatively pure limestones apparently contain only a little or none at all.

There is another aspect that merits consideration, namely, the existence in syenite and in nepheline-free and nepheline-bearing paragneisses of "lepidomelane" and "hastingsite" of identical nature. Previously, that association has been interpreted as a criterion of consanguinity of the granite, syenite, "shonkinite," "foyaite," and so forth. Under the present hypothesis, that distribution of the ferromagnesian minerals of rather unusual characteristics is logically explained as the result of contamination of the granite, by inclusions of the paragneisses whose composition was such that "lepidomelane" and "hastingsite" were formed (or which already contained those minerals).

Composition of nephelinizing solutions.—The field and laboratory work have produced three chief items of interest, which must be considered in the discussion of the mode of origin of the nepheline rocks: (1) The nepheline rocks were formed *in situ* by some process of replacement, and whether or not we can at present suggest the chemistry and mechanics of the process forming them, that fact remains. (2) The aluminosilicates of many of the nepheline rocks replace calcite. (3) There is a reciprocal relation between Al and Fe, such that, as Al_2O_3 increases, Fe_2O_3 decreases and, as Al_2O_3 decreases, Fe_2O_3 increases. In the rocks containing appreciable quantities of nepheline the sum-R_2O_3 approximates 30 per cent; in lower-grade rocks the sum-R_2O_3 is less, but the ratio Fe/Al increases rapidly with decreasing Al_2O_3. Paralleling this relation is that between lime and alkalis. Although there may be danger of overemphasizing the relation between Fe and Al, it does appear to be more than fortuitous.

Irrespective of the exact source and accepting the impure calcareous nature of the rocks prior to their alteration, it is obvious that soda in some form has been added. Generally soda-rich derivatives of granitic and syenitic magmas (and it is from such magmas that a soda-rich derivative is to be expected) are presumed to be, at the same time, silica-rich, as expressed empirically by "Na_2SiO_3." The presence of much silica immediately renders unlikely the ultimate formation of feldspathoids, unless that silica is first combined with some other substance ("desilication").

The petrographic evidence is strong for the development of nepheline and albite as replacements of calcite; it is impossible to escape the conclusion that calcite has played some prominent role in the formation of the nepheline rocks. If the nephelinizing solutions were actually albitizing solutions which underwent desilication through reaction with $CaCO_3$, perhaps along the lines suggested by the following equation:

$$NaAlS_3iO_8 + 2CaCO_3 = NaAlSiO_4 + 2CaSiO_3 + 2CO_2\,,$$

then the reaction was outwardly similar to Daly's postulate.[37] The difficulty now,

[37] Note that other reactions may be written in this fashion, such as $CaCO_3 + 4NaAlSi_3O_8 = 2NaAlSi_3O_8 \cdot CaAl_2Si_2O_8 + Na_2SiO_3 + SiO_2 + CO_2$, which is a *silicating* reaction. There is, of course, no

as always, is to explain the whereabouts of the lime silicate which was formed—in other words, there is no evidence of such a reaction. It is not easy to claim that reaction products have been removed, since lime tends to form rather insoluble compounds with silica; but either it was removed or it did not react in that fashion. If it did not, the nepheline-producing solutions were of one of two types: (1) they contained nepheline or the ingredients requisite for the formation of nepheline, in appropriate proportions, or (2) they were deficient in silica, and a desilication reaction was unnecessary, the silica of the sediments taking part in the reactions with the incoming soda and alumina. In connection with the first alternative, it has been suggested, as a way out of the difficulties posed here and elsewhere by the apparent nonexistence of lime-silicate reaction products, that desilication occurred at depth and that the magma thus formed then migrated upward. Even if that were so, the fact remains that that magma did not invade the sediments and solidify as an entity in the fashion of normal magmas; it replaced the rocks in what must have been a slow and dynamically tranquil manner. If this desilication occurred, the products of the reaction were not exposed, nor were they encountered in a considerable diamond-drilling program.

Were the solutions essentially carriers of soda and alumina, i.e., deficient in silica, the process would be more simply a reciprocal reaction between the solutions and the rocks into which they permeated, whereby the rocks gained in soda and alumina and lost lime (and iron?).

evidence that this ever occurred or that it could occur, but the first replacement of calcite appears to have been oligoclase.

The abundance of calcite of late generation, especially in pegmatitic zones, suggests that CaO and CO_2 remained in close association, if not actually as $CaCO_3$, which might be possible in solutions low in silica. If that was the case, lime silicates never did form as a result of a desilication reaction, and the calcite which was replaced by feldspar and feldspathoid later reappeared simply as calcite.[38]

It is known that limestones, otherwise fairly pure, have albite and nepheline locally developed. This is especially (but not invariably) true adjacent to pegmatites, and, since the pegmatites may not be strictly similar to the gneisses in mode of origin, perhaps this is not conclusive; nevertheless, in such occurrences it is shown that soda, alumina, and silica have combined to replace calcite.

The rocks of the York River and Bancroft areas appear to be of the same general horizon of sedimentary material. Therefore, at one time they were presumably of the same general nature, i.e., impure lime rocks but varying from place to place in degree of impurity. If the rocks were originally similar, the York River gneisses may now resemble most closely the original composition of the sediments. That suggests that alumina and alkalis have been added and that lime and iron have been subtracted. This seems to have been the case in the Bancroft area in particular, where the iron content of the gneisses is lower than in York River rocks but where there are local concentrations of magnetite. Some rocks near Tory Hill are rich in nepheline but also contain a high percentage of magnetite; nevertheless it is the general

[38] This raises the question of the nature of solutions that would dissolve calcite but precipitate nepheline, also acid-soluble to some degree. Perhaps the solution of $CaCO_3$ was aided by retention of CO_2 in the system under more or less neutral conditions.

case that alumina and iron bear a rough inverse relation to each other.

The iron content of the nepheline rocks has been the subject of much previous discussion; its origin remains in some doubt but can be limited to two possibilities: (1) it existed in the original sediments and in some places was merely recrystallized, in others was removed to be redeposited elsewhere, or (2) it was brought in with the nephelinizing solutions and deposited during this process. It is evident from the foregoing discussions that the first is considered the more reasonable conclusion. Since iron does form volatile compounds and transportation by or as volatiles has been accepted in certain instances, there is a possibility that it has in this case been associated with volatiles at some stage. The difficulty now is to reconcile the replacement of $CaCO_3$ by alumina-rich silicates and the inverse relation between Al and Fe.[39] It does not seem that there would be such a relation had the iron been introduced. The relation, however, may be taken as evidence that alumina has been introduced, and possibly some kind of balance was attained during the process of nephelinization between the silicate radical and the R_2O_3 substances. It may even be that that balance determined the ultimate degree of nephelinization.

Now, at any rate, the Al_2O_3 and Fe_2O_3 exist, for the most part, in separate and specifically unrelated minerals. The bulk of the iron oxides occurs as magnetite, and, furthermore, much of the magnetite appears to have been developed late in the nephelinization process.

However, a control of some kind on the process by the original composition of the sediments is strongly suggested. This statement implies that nephelinization occurred in rocks of rather definite constitution and that chemical factors, in addition to physical factors, played a part.

The possible importance of volatiles in the concentration and transportation of alumina and alkalis has been stressed by both C. H. Smyth,[40] and Gillson.[41] Daly and, later, Foye,[42] who elaborated on the theory, had suggested that the volatiles resultant from a desilication reaction might concentrate alumina and alkalis in the upper regions of the magma chamber. Smyth and Gillson, however, conceived the volatiles to be juvenile rather than the result of reaction, for instance, between granite and limestone.

The rocks containing nepheline are, then, pictured as originally ferriferous, siliceous, lime-bearing sediments. It is more logical to assume the addition of soda and alumina rather than the addition of soda alone, although some alumina undoubtedly existed in the rocks at the start. To what extent silica was added is not certain, but it must have been introduced to some degree. In purer varieties of limestones adjacent to pegmatites, silica has certainly been introduced; in fact, the minerals albite and nepheline appear to have been introduced there as such. The role that

[39] A good deal of speculation in an attempt to explain the relation Fe : Al could be recorded, but it is most definitely speculation. For instance, since it appears that Fe must be linked with Al or with the carbonates that were replaced by Al (etc.), is it possible that at one time the Fe existed as FeO in carbonate of a sideritic nature, that it was for some reason unstable at temperatures and pressures attained during the replacement process ($FeCO_3$ dissociates at a much lower temperature than does calcite), and that it was in part oxidized to yield magnetite and in part dissolved, to re-form again later as magnetite?

[40] "The Origin of Alkaline Rocks," *Jour. Geol.*, Vol. XXXVI (1927), p. 40.

[41] P. 473 of ftn. 25.

[42] W. J. Foye, "Nepheline Syenites of Haliburton County, Ontario," *Amer. Jour. Sci.*, Vol. XL (4th ser., 1915), p. 424.

volatiles have played is also uncertain, but the mineralogy and the textures testify to their activity; volatiles presumably would be far more mobile than liquids alone and would also be more capable of traversing minute rock openings.

Source of the nephelinizing solutions.—If the nepheline rocks are the result of replacement, somewhere there must have been a source of supply for the agents that carried out that replacement. The following possible sources may be suggested:

1. Gabbro, diorite (York River, Madoc area, etc.). There is no evidence forthcoming of any genetic connection between the gabbro or diorite of the Bancroft area and the nepheline rocks. However, Adams and Barlow indicated a nepheline gabbro on their map, and W. G. Miller[43] described a corundum-plagioclase-hornblende rock, which he believed was related to the nepheline rocks.
2. Harbingers of the exposed, younger granite, the altered rocks later being invaded by further advance of the parent-magma. Such relations are not unknown.[44]
3. Some granitic or syenitic body that perhaps never manifested itself by intrusion in the zone of observation or, if it did, has since been masked by the younger granite.

The evidence pointing to the origin of the solutions is scanty, but we have this much information: that the introduced materials contained soda and alumina and apparently not much silica. The possibilities as to the source of soda- and alumina-rich solutions are several, but it is most logical to expect that the immediate source of supply was a salic body; and if that body were itself a derivative by fractional crystallization from a more basic magma, then it would be equally logical to expect a concentration of volatiles in that salic derivative. The one-time activity of volatiles in the formation of the nepheline rocks has been attested by mineralogy and texture in several instances.

If the reported occurrences of basic rock containing nepheline and corundum are truly igneous and intrusive, it would be of interest to consider the possibilities of a genetic relation between the soda-alumina emanations and those basic rocks. Indeed, unless those rocks are proved otherwise than intrusive, they must be included in the broad picture. It is perhaps interesting to note further that anorthosites, containing in the neighborhood of 30 per cent Al_2O_3, occur in the general region and are related to definite gabbroic intrusives.

However, with the present information, it seems preferable to suggest only that the soda and alumina were immediately derived from a granitic or syenitic source, a source which itself is of uncertain origin and nature.

FURTHER COMPARISON OF YORK RIVER, BANCROFT, AND BLUE MOUNTAIN AREAS

Although field relations have indicated that the nepheline rocks were in all probability developed from a persistent horizon of sedimentary material, the mineralogical differences between the rocks of the areas are noticeable. Those differences are considered to be due, in the main, to the following five factors:

1. Original variations in the sediments
2. Arrest of the process of nephelinization at various stages
3. Differences in physicochemical conditions attained, resulting in contrasted mineral assemblages
4. Amount of deformation, i.e., availability of structural openings
5. Degree of modification of the nepheline rocks by the younger granite

[43] "Notes on the Corundum-bearing Rocks of Eastern Ontario," *Amer. Geol.*, Vol. XXIV (1899), pp. 276–82.

[44] H. C. Horwood, "Granitization in the Cross Lake Area, Manitoba," *Trans. Roy. Soc. Canada*, Vol. XXX, Sec. IV (3d ser., 1936), pp. 99–117.

The Bancroft rocks are richer in nepheline, on the whole, than are the York River rocks. It has been suggested that (making allowances for original compositional differences) the York River rocks have undergone less nephelinization than have the Bancroft rocks. Following this hypothesis, it might be conjectured that the Blue Mountain rocks, which least resemble sediments, are furthest advanced in the nephelinization process. It is interesting to note that the York River rocks show least contortion, the Bancroft rocks considerably more, and that the structure that is visible in Blue Mountain rocks is a highly contorted one.

The fifth factor must be considered, since the action of the younger granite may have resulted in further mineralogical changes; it is accepted, indeed, that it has done so, namely, in "albitizing" nepheline, introducing microcline, and being responsible for much of the alteration of nepheline to hydrous silicates. A part of the higher silica content of the Bancroft area rocks is therefore due to action by the younger granite. The York River rocks, which are, so to speak, insulated from the granite to the west by beds of limestone and other sediments, appear to be less affected than are the rocks of the Bancroft area. The comparison may best be illustrated in the following fashion:

York River.—Fresh nepheline; potash feldspar scarce, and rocks insulated from the granite

Bancroft area.—Locally much nepheline altered; potash feldspar more abundant, concentrated near joints, faults, and granitic and syenitic dikes; rocks not everywhere protected from the granite

Blue Mountain.—Much nepheline altered; potash feldspar important; rocks surrounded by granite-syenite

The inclusion here of characteristics of Blue Mountain rocks is not intended to imply that the origin of those rocks is taken for granted as being similar to that of rocks of the other areas. In the brief study made of only a part of the Blue Mountain deposit, no evidence was seen which is conclusive one way or another, although the general outline of the alkaline mass, the proved contortion within it that resembles folded stratification, and the close association with certain paragneisses might be construed as favorable to the replacement theory. The apparent distribution of corundum also suggests that it is due to compositional control during the alteration of banded rocks. It was reported, but never verified, that at the southernmost tip the nepheline rock "grades into micaceous paragneisses." Therefore, comparison with other areas is definitely interesting.

NEPHELINE PEGMATITES

The nepheline pegmatites of all areas visited present rather conflicting relations. Their texture is typically pegmatitic, the coarseness of grain size suggesting that volatiles were important in their formation. The common association of calcite-rich bodies have suggested that $CaCO_3$ was also important. Most, if not all, of the substances present in pegmatites are present also in the gneisses.

The pegmatites obviously formed after the nepheline rocks. Some may be explained as replacements, some as recrystallizations, some as intrusives. Certain determination of their origin will come only as a result of much detailed study. The available data are worthy of consideration:

1. Pegmatites cut or replace nepheline rocks.
2. Pegmatites are cut by satellitic dikes of the granitic intrusions.
3. The grain size, contacts, and mineralogy in most cases attest to the presence of volatiles.
4. The common presence of rare elements indi-

cates that those substances were actually concentrated in some medium.

5. Some bodies occur entirely in nepheline rock, some in limestone, and others appear to traverse several types of rock.

We might theorize that some of the pegmatites represent recrystallization ("regeneration") *in situ* in the presence of introduced materials acting as a flux or lubricant; and for some this may be a suitable explanation. But for those pegmatites which replace limestone, the very use of the word "replacement" implies that some agent was available to carry out that process. For those bodies it might be proposed that they were formed in a fashion similar to the development of the nepheline gneisses and that the ultimate concentration of volatiles simply led to pegmatitic textures. But a third group exists, and those appear to have been emplaced by actual intrusion. An example occurs in the York River area, where it is indicated, by surface and drill-core evidence, that nepheline pegmatite truncates the structure of the enclosing gneisses, which are both nepheline-free and nepheline-rich.

There are, then, three types of pegmatite; but all three may be due to the same action, which was in some instances very local and relatively weak but in others was advanced to such a degree that a body of liquid was produced and ensuing movement of the liquid took place in directions determined by structural features.

CONCLUSIONS

This paper is not to be taken as an expression of general dissent from the limestone-syntexis theory. As pointed out by S. J. Shand in a recent publication,[45] there are numerous localities where alkaline rocks are closely associated with limestones, on the one hand, and quartz-bearing igneous rocks, on the other; and in many the evidence is in favor of desilication. We have, however, drawn attention to some earlier misinterpretations in the particular area covered by this study; and, as a result of the corrections, the applicability of the syntexis theory in that area is rendered decidedly doubtful. There is no apparent reason why alkaline rocks cannot form in more than one fashion; in many areas, feldspathoidal magmas are satisfactorily accounted for only by limestone syntexis; in the Bancroft area, the "alkaline rocks" have formed through replacement, and the evidence is not entirely indicative that the replacement was carried out by *nepheline-bearing* solutions that might have formed elsewhere by desilication. The evidence is rather that the solutions were *nepheline-forming* by virtue of the substances they contained and the substances available in the rocks. We cannot show that solutions greatly depleted in silica, even to such a degree that there was insufficient silica to form nepheline, did not originate elsewhere by a reaction similar to the desilication reaction.

In summary, our conclusions may be marshaled in the following fashion:

In the Bancroft and adjacent areas certain horizons of impure calcareous sediments, containing silica, iron, and some alumina, have been modified by the action of a process termed "nephelinization." The process was mechanically analogous to granitization but was chemically different. The nephelinizing solutions at one time or another carried, in particular, soda and alumina, with quantities of volatiles, including H_2O, Cl, P, and others. The exact source of the solutions

[45] "The Present Status of Daly's Hypothesis of the Alkaline Rocks," *Amer. Jour. Sci.*, Vol. CCXLIII*A* (1945) (Daly Volume), pp. 495–507.

is indeterminate, but it was probably a granitic or syenitic magma that is not now recognizable and whose origin and nature are also a matter of question. No definitely intrusive bodies containing nepheline have been observed, excepting a few pegmatitic examples; recrystallization and silication adjacent to fractures have produced anomalous relationships in some instances.

Structural features played an important role in the process; the zones of intense nephelinization were determined by subsidiary folds on the limbs of the major fold.

Most of the pegmatites appear to be replacement bodies, formed, to an unknown extent, through recrystallization ("regeneration") in the presence of "lubricating" mineralizers. Locally, bodies of liquid may have been formed that manifested themselves as pegmatites, which contained variable amounts of nepheline and exhibited intrusive characteristics.

There remain several questions that are imperfectly answered, but they are more or less incidental to the main theme of this paper.

The following succession of events is postulated:

1. Deformation and metamorphism of a series of sediments, consisting of limestones, dolomites, and various rocks of calcareous graywacke type, with the resulting formation of folded structures
2. Formation of nepheline-bearing paragneisses
3. Formation of nepheline pegmatites
4. Intrusion (localized by existing structural features) of granitic magma, with four secondary effects: (*a*) formation of border or contact hybrids from paragneisses; (*b*) formation of syenitic border zones by reaction with several kinds of rock; (*c*) silication (albitization) of nepheline rocks adjacent to rock openings and bedding contacts; and (*d*) some folding and faulting

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ON THE ORIGIN OF CONTINENTS AND OCEAN FLOORS

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ABSTRACT

From the concept of permanence the fundamental question arises as to how the distribution of continental and oceanic sectors came into being. Three groups of theories are discussed: (1) theories starting with a primary surface layer of basaltic composition; (2) theories starting with the resonance theory of the moon's origin and considering the result of such a hypothetical happening on a sialic surface layer of continental thickness; and (3) theories considering the influence of convection currents on a surface layer of sialic composition.

INTRODUCTION

An examination of the Atlantic and Indian oceans and a comparison with the available geological and seismic data show that the bottom of these oceans probably consists of sialic material. On the other hand, the floor of the Pacific appears to be built up of a rigid crystalline layer of basic rocks (crystalline sima). The average depth of the Atlantic appears to be 4–5 km., whereas the North Pacific is generally 1 km. deeper. The explanation seems obvious: viz., the deep depression of the Pacific is controlled by the simatic nature of its bottom; the 1,000-meter higher level of the Atlantic floor is brought about by the presence of a sial-sheet; and the still higher level of the continents is the result of the latter's composition of sial-sheets, which are considerably thicker than the sial-flake under the Atlantic.

The available morphological, geological, and geophysical data cannot be considered as harmonizing either with the hypothesis of a large continental drift in comparatively recent times (Fig. 1, *B*) or with the hypothetical assumption that the floors of the Atlantic and the Indian oceans originated in the Paleozoic, or at an even more recent date, as a result of stretching of continental blocks (Fig. 1, *C*). The hypothesis of large submerged blocks does not agree with the water economy of the oceans (Fig. 1, *A*). For, if the volume of water of the oceans is assumed to have remained relatively stable, the continents would have had to be permanently flooded prior to the foundering of the continental blocks; and this conflicts with all that is known of their geological history. The alternative, viz., that the volume of the oceanic waters has increased by a few cubic kilometers per year, is equally improbable.

The configuration of the continents and oceans has not escaped frequent alterations. Some parts have been submerged, even though such regions as Appalachia, Cascadia, and Scandia were no larger than "borderlands," as Schuchert called them. The idea of permanence is consequently untenable in its extreme sense. But we can speak *cum grano salis* of permanence of the oceans and continents so long as we refrain from constructing huge submerged continents.

These opinions have been stated elsewhere[1] at greater length. The concept of permanency of the oceanic receptacles implies the conviction that these major depressions date from some very early

[1] J. H. F. Umbgrove, *The Pulse of the Earth* (The Hague: Nijhoff, 1942), chap. vi.

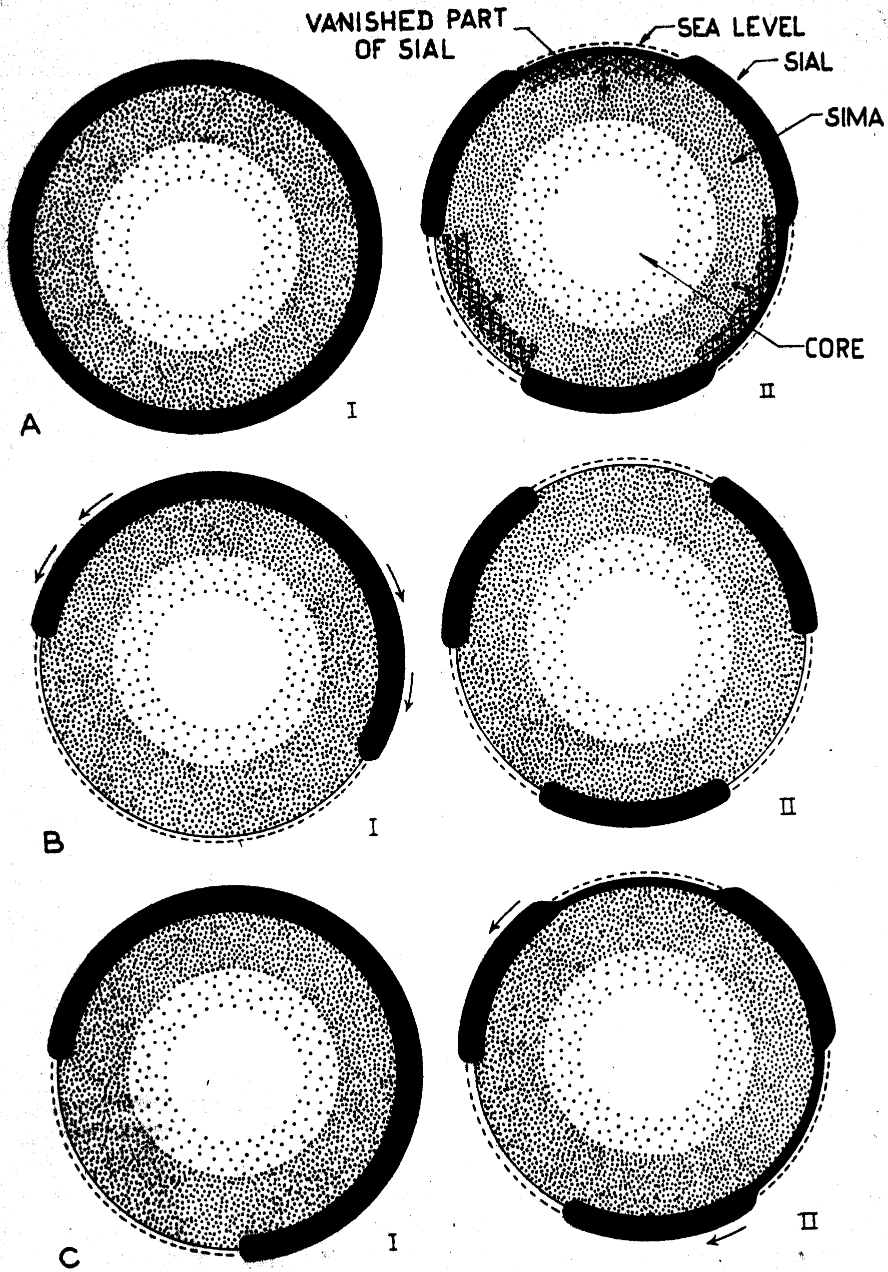

FIG. 1.—Schematic representation of the origin of continents and oceanic receptacles according to the hypotheses of Suess and Haug (*A*), Wegener (*B*), and Bucher (*C*). *I*, Paleozoic condition; *II*, post-Paleozoic movements.

period of the earth's history and that their position has remained essentially unchanged since. But now the question arises as to when and how the "permanent" distribution of continental and oceanic sectors came into being in such a way as to display an antipodal arrangement and a "tetrahedral" plan. What were the factors that caused the concentration of a northern belt of triangular continents, alternating with a southern belt of oceanic units distributed "like a pair of cogwheels with interlocking teeth"?[2] As a matter of fact, thinking of the terrestrial processes that must have operated in the earliest days of our globe's infancy means to enter inevitably a domain which is characterized by scanty available data and therefore widely open to speculation.

It is believed by some geologists, especially by petrologists like Lawson and Rittmann, that the earth's surface in its initial stage was composed of a basaltic melt. It will be interesting to see how they deduced sialic continents from a primary homogeneous surface layer of basic composition.

A second group of theories lays stress on a happening of cosmic importance—the birth of the moon out of the body of the earth. In this group will have to be considered the theories of Osmond Fisher, Pickering, Escher, etc. These students start with a globe surrounded by an outermost layer of sialic rocks of continental thickness, and they try to deduce the origin of continental bucklers and oceanic depressions from the cosmic catastrophe which gave rise to the genesis of the moon in the manner suggested by G. H. Darwin.

Then, in the third place, we will start anew with the idea of a world-encircling layer of sial and try to deduce the desired distribution of continents and oceans without the aid, however, of the hypothetical events of the lunar catastrophe. Some efforts in this direction have been presented recently by the present author and still more recently by Vening Meinesz.

THEORIES OF A PRIMARY SURFACE LAYER OF BASALTIC COMPOSITION

In 1932 A. C. Lawson formulated a theory to account for the formation of continents from a crust which originally consisted of sima only.[3] In his opinion an upper layer of basaltic rocks covered a deeper substratum of dunite. Basaltic continents were produced by orogenic stress. Erosion products from these basaltic continents were carried to the primeval oceans; the basic parts went into a state of solution, while the sialic elements became concentrated; and when these waste products sank sufficiently, they were fused together, so as to form acid granitic rocks. By this process the continents became continually more sialic. Then the sialic material differentiated into a double layer—granite above and diorite below.

Seven years later the Swiss petrologist A. Rittmann[4] introduced a theory which in its main elements is closely akin to that of Lawson. It differs from it, however, in one respect. According to Rittmann, the sialic waste products which assembled in the primeval oceans (Fig. 2) were magmatized by the gases emanating from the substratum. By this process they grew specifically lighter. To restore isostatic equilibrium the

[2] J. W. Gregory, "The Plan of the Earth and Its Cause," *Geog. Jour.*, Vol. XIII (1899), p. 227.

[3] "Insular Arcs, Foredeeps and Geosynclinal Seas of the Asiatic Coast," *Bull. Geol. Soc. Amer.*, Vol. XLIII (1932), pp. 353–82.

[4] "Die Entstehung des Sials," *Geol. Rund.*, Vol. 30 pp. 52–60, 1939.

sialic floors of the primary oceanic receptacles emerged to form sialic continents. On the other hand, the original bucklers of alkali-basalt subsided to form the bottom of the present oceans!

A weak point in both these theories is the formation of the primary basaltic continents. For, in the first place, it is not clear how these protuberances could have formed with preservation of isostatic equilibrium. Nor is it clear how over, the primary disturbance causing the genesis of continental domes out of the basaltic surface layer comes like a *deus ex machina*. Without accepting this initial stage the further deductions of the theory become impossible. Finally, the theories leave the question of the tetrahedral or antipodal plan of terrestrial elements untouched. Nor do they explain the existence of three hypsometric levels, nor the remarkable structural

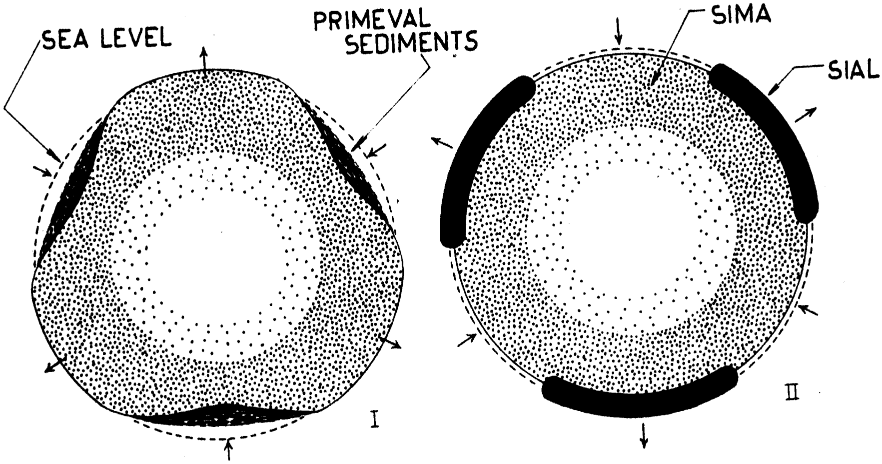

FIG. 2.—Schematic representation of the origin of the continents in the early pre-Cambrian, according to the hypothesis of Rittmann.

these units could have risen isostatically during the long-continued rise above sea-level necessary to provide the primeval oceanic depressions with thousands of meters of erosion products.[5] More-pattern of the bottom of the Atlantic, etc.

THE RESONANCE THEORY OF THE MOON'S ORIGIN: CONSEQUENCES ON A SIALIC SURFACE LAYER OF CONTINENTAL THICKNESS

It was G. H. Darwin who announced the hypothesis of the moon's origin out

[5] In this respect A. Wade's theory of continental spreading, which is that the spreading starts from a basaltic surface, has some slight advantage. His primeval polar continents were thought to become bare land by the hypothetical process of a retraction of the oceans from the polar areas toward the equatorial belt. The water was supposed to pile up in that region as a result of (1) the greater speed at which the earth rotated on its axis and (2) the greater gravitational pull by the moon, which then was nearer to the earth. According to Wade's theory, the polar continents became covered by a sheet of sial by the "agencies at work which would affect oxidation, hydration, erosion and sedimentation." And he continues: "As soon as these sial-sheets became thick enough and sufficiently consolidated to upset the hydrostatic equilibrium at the poles, both sheets would begin to move and the problem resolves into one concerning two fluids—a lighter one resting on one more dense" ("A New Theory of Continental Spreading," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XIX [1935], p. 1808).

of the body of the earth. Several geologists have tried to imagine the consequences of such a hypothetical birth upon the structural history of the earth's surface layers. If we accept the resonance theory of the moon's origin, it seems highly probable that a great part of the earth's outer shells entered the moon's formation. But what happened to the remaining sialic matter of the earth? There are two possibilities: viz., either the terrestrial remnants of sial were able to flow out and unite again as one continuous shell, enveloping the entire world, or they were unable to do so, being too rigid. The last possibility is basic to the theories of many authors. In their opinion the earth was originally enveloped by a sialic shell of continental thickness. After the moon's disruption the remaining sial-fragments of the earth would have formed our continents, floating on the heavier simatic substratum that forms the bottom of the oceanic receptacles (Fig. 1, *B*). Long ago, the question was raised whether the Pacific might not be considered as a scar brought about by the separation of the moon.

Practically the same idea can be found in the theories of Osmond Fisher, Taylor, Wegener, Schwinner, Escher, and Mohorovicic. The two last-named authors[6] even tried to calculate the thickness of the lunar sial by computing the mass of terrestrial sial that originally filled the gaps of the oceanic sectors. (Both assumed an original crust of continental thickness, and no account was taken of the presence of the sial-flakes of the Atlantic and Indian oceans.)

It is, at all events, clear, however, that neither the continents nor even their so-called "nuclei" (representing the innermost structures of the continents) should be regarded as undisturbed remnants of that distant and turbulent period in our planet's infancy. The "acid slags" had from the early beginning a very complicated history, and the continents (parts of which have been breaking down until quite recently) formerly occupied a more extensive area than they do at present. We know, moreover, that the history of the submarine relief of the oceans is a far from simple one. Another point is that the bottoms of the Atlantic and Indian oceans differ considerably from the floor of the Pacific.

The last important point is, however, taken into account by W. H. Pickering's hypothesis.[7] For, first, his supposition that the scar left on our globe's surface when the moon was torn from the earth's body must be represented by the Pacific explains why that ocean bottom is free of sial. Second, he supposes the scar originally to have been much larger than the present Pacific. "Three-quarters of this crust was carried away," he wrote, "and it is suggested that the remainder was torn in two to form the eastern and western continents." So we could very well imagine that *at this stage* some continental masses drifted apart and that between them the floors of the Atlantic and Indian oceans formed as a result of stretching. Here Pickering's theory is much to be preferred to Wegener's and Du Toit's theories of continental drift. For, in a previous publication[8] much

[6] B. G. Escher, "Moon and Earth," *Proc. Kon. Acad. Wetensch. Amsterdam*, Vol. XLII (1939), pp. 127–38; S. Mohorovicic, "Das Erdinnere," *Zeitschr. f. angew. Geoph.*, Vol. I (1925), pp. 330–83; and *idem*, "Über Nahbeben und über die Konstitution des Erd- und Mondinnern," *Gerland Beitr. zur Geoph.*, Vol. XVII (1927), pp. 180–231.

[7] "The Place of Origin of the Moon: The Volcanic Problem," *Jour. Geol.*, Vol. XV (1907), pp. 23–30, and "The Separation of the Continents by Fission," *Geol. Mag.*, Vol. LXI (1924), pp. 31–35.

[8] Umbgrove, *op. cit.*, p. 96.

stress was laid on convincing arguments which show that, if the floor of the said oceans originated as a result of stretching, this process must have occurred during the early pre-Cambrian and decidedly not since Cambrian, or still less in post-Carboniferous times, as Wegener *cum suis* wished us to believe.

But again the question arises: How did these sial-flakes, drifting apart like large ice floes, come to be settled down in their peculiar tetrahedral arrangement?

Another question of primary importance, however, is: Why should the sialic material have flowed out to form a continuous shell on the moon and not on the earth? The following points should not be forgotten in this connection.

It is questionable, although quite possible, that, prior to the postulated disruption, the sialic material had differentiated into the outer parts of our globe but was not yet in a solid state. Everyone will admit that the outer shells of the earth should have responded readily to deforming tidal forces before, as well as after, the moon's separation. It will also be admitted, if we follow this hypothesis, that part of these outer shells shifted toward the moon and that the scar of the separation was closed smoothly. Moreover, it seems probable that when the earth, recovering from its amputation, was molded into its new shape, the simatic layers—even the uppermost—formed a fluid mass uniting into a continuous shell. It seems, therefore, quite unreasonable to suppose that the thin upper layer of sial would have been the only one incapable of reacting in the same way.[9] The preceding considerations are based on the resonance theory of the moon's origin and are valueless if we accept the opposite view, namely, that the moon and the earth formed simultaneously as two separate bodies.

THEORIES CONSIDERING THE INFLUENCES OF CONVECTION CURRENTS ON A SURFACE LAYER OF SIALIC COMPOSITION

Once more our considerations may be based on the supposition that the earth was initially enveloped by a continuous sialic layer, gradually solidifying and floating on a denser basic substratum.[10] It may be that this layer formed after the moon's disruption, but it might similarly be assumed that the moon had not severed from the earth.

According to the present author, the only plausible way in which continental blocks might have originated from a world-encircling sialic layer, growing gradually cooler and solidifying, is that a process of thickening occurred, resulting from folding and drifting, due to the action of convection currents.

This process shortens the sialic layer, and sial-free parts (such as large portions of the present Pacific area) were therefore formed. Figure 3 *A–C* shows diagrammatically how a continent may possibly have originated through periodical buckling and drifting of an originally thin sialic layer enveloping the whole earth.

It may be that during the process of the drifting of these primordial continents a sial-sheet was torn into two or

[9] Even the lighter simatic material would have been lacking in the Pacific sector, according to Schwinner, and this would have prevented the sialic layer from covering this area. The fact, however, that the Pacific's volcanoes are built up of basaltic material clearly shows that this opinion cannot be upheld.

[10] A similar concept of a layer of sial which originally encircled the world is held by Bowie; Geszti; Daly (1938), p. 176; and Wegener (4th ed., 1929), p. 207.

more parts, each moving in a different direction and producing one or more thinly stretched sial-flakes between them (Fig. 3, *D*). In this way (and only during these primordial times) a thin sial-sheet like that which probably exists under the Atlantic may possibly have originated as a result of stretching of either a primordial continent or the intervening primary sial-layer. There is reason to believe that this process actually happened. For, if the sial of our present con-

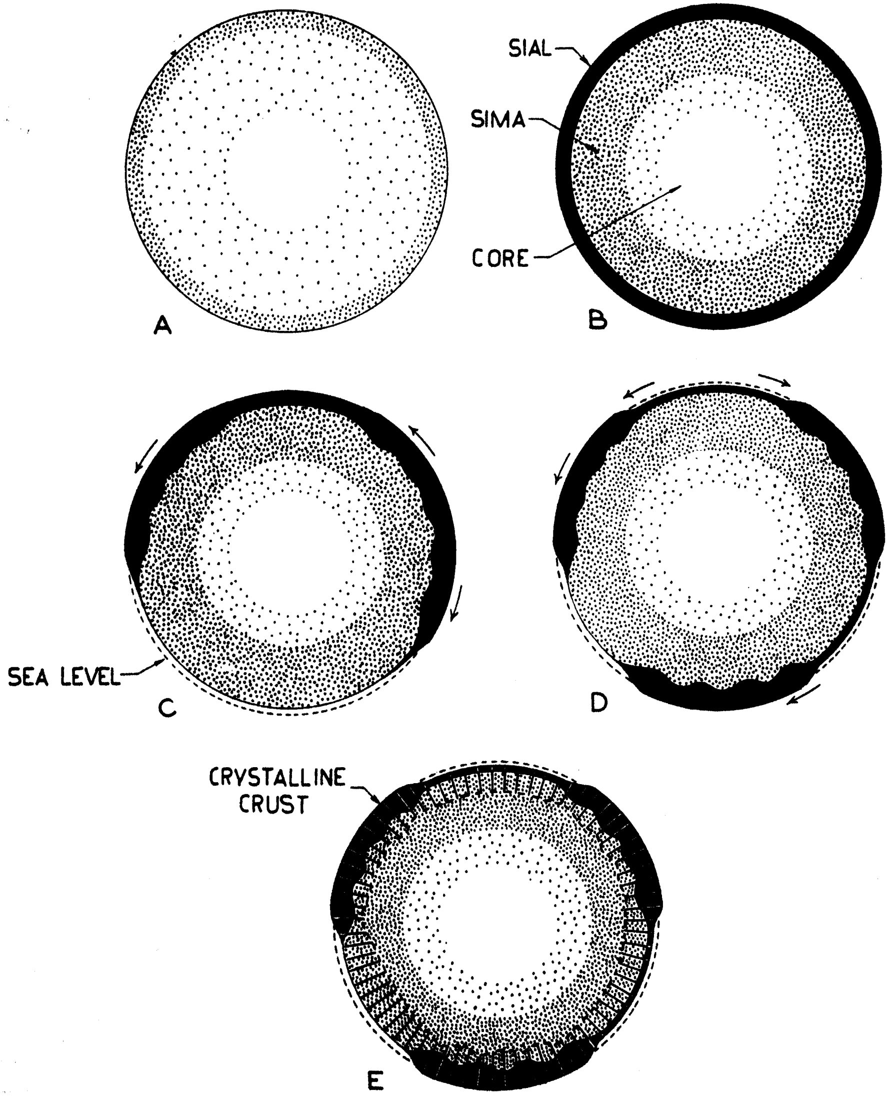

FIG. 3.—Schematic representation of the origin of continents and oceanic receptacles in the early pre-Cambrian by a process of buckling and drifting of an originally sialic layer enveloping the whole earth.

tinents were imagined as spreading out as thickly as the sial-layer of the Atlantic, it would probably cover a larger area than that of the present sial-free ocean bottoms. A floor such as that of the Atlantic cannot, therefore, be regarded as a remnant of the primary world-encircling sialic shell. On the contrary, it would seem to have grown thinner as a result of stretching during the early pre-Cambrian. It would be impossible to say, just now, whether a fragment of the primary sialic layer of original thickness exists in some part of the world today.

It is obvious that this process must have attained its most important effect in the early pre-Cambrian, since the whole later process of buckling and folding of the continents is known to have evolved only in these existing pre-Cambrian bucklers. This is, indeed, remarkable and will have to be examined before any other features are discussed.

In the beginning the continents grew steadily larger; but this has not been repeated since at least the Cambrian, or probably even earlier times, as the geosynclines and folded chains that are known to have formed since then originated in a basement which had already been folded previously.[11]

Hence we cannot escape the conclusion that some event of fundamental importance must have occurred during the early part of the earth's history, causing the surface history of primeval times to differ from that of subsequent periods. By this we mean that from a certain critical moment onward continental growth in a "horizontal" direction ceased. The most plausible explanation seems to be that the world-encircling solid crust had become so thick that subsequent growth was no longer possible. Such youthful caprices as are illustrated in Figure 3, *A–D*, may be expected to have ended as soon as the earth had attained a physical state more or less resembling that which it has at present (Fig. 3, *E*). From that time onward the terrestrial forces were imprisoned and became operative as subcrustal processes.

At that time the crust consisted of basic rocks in the sial-free parts of the surface just as it does now; and it may have contained both sialic and simatic rocks in those regions of the world where sial-flakes were present. It must have been of varying thickness, though it need not, of course, have equaled its present-day thickness. We will call this state the "consolidated surface of the earth." A few years ago W. Bowie[12] formulated his opinion regarding a primeval process of crustal buckling as follows: "It is impossible on a molten earth gradually cooling to have the light material which must have been present around the whole earth, pushed together into great masses to form continents. There is no force available inside or outside the earth which could have caused such a segregation of surface matter."

As mentioned before, the process of folding and drifting of the sialic surface layer is ascribed by us to the action of convection currents. Their periodical occurrence must at one time have found the sial-sheet cooled and solidified to such a degree that the result was continental thickening.

If the foregoing hypothesis may be said to contain a germ of truth, the problem of the continents and ocean floors would consequently be associated with periodic phenomena of crustal folding, which had, however, already produced their main results in the early pre-

[11] A fuller illustration of the preceding consideration will be found in chap. ii and the Appendix of Umbgrove, *op. cit.*

[12] "The Origin of Continents and Oceans," *Sci. Monthly*, Vol. XLI (1935), p. 447.

Cambrian. A few points will now be examined more closely.

Let us consider the moment that these primeval surface features became petrified, as it were, by the formation of a world-encircling solid crust of sufficient thickness.

The noteworthy structural pattern of the floor of the Atlantic and the surrounding continents probably originated in the early pre-Cambrian, for the old structural lines repeatedly influenced tectonic phenomena in later times. It might therefore be asked whether it is not obvious that this ancient pattern dates from the period of consolidation of a solid crust. In the preceding paragraphs we stated that three favored levels occur on earth, represented by (1) the continental surface, (2) the floor of the Atlantic, and (3) the bottom of the Pacific Ocean. It need hardly be said that these features fit well with our working hypothesis. The difference in the level of the primeval floors of the Pacific and Atlantic is seemingly due to the difference of the materials composing each floor.

On the other hand, buckling of the primordial sialic crust was responsible for the continental thickenings. Their remarkable thickness and high level, as compared to that of the bottom of the Atlantic, is controlled by five factors, viz. (1) the thickness of the original world-wide sialic layer, (2) the compressive forces during the periodic phases of early pre-Cambrian buckling, (3) the leveling effect of subaerial erosion, (4) the pre-Cambrian stretching of sial-sheets of the Atlantic type, and (5) the local thickening of the continental basement complex as a result of the formation of later geosynclines and mountain belts.

The above considerations indicate the main outlines of the new working hypothesis. I do not wish to suggest that this hypothesis solves the intricate problem of the ocean floors. I merely followed a line of thought which had hitherto been neglected; and, as all the previous hypotheses are deficient in many respects, the new hypothesis may stimulate others in their efforts to unravel the mystery of the ocean floors. I fully realize how many difficulties are inherent in this new aspect of the old problem.

It will be seen that some of the most attractive aspects of the theory were explained as well by Pickering's hypothesis. And the weak points in both theories are again the same. For no adequate explanation was given for the antipodal distribution of the major units of the earth's surface, nor for the triangular shape of these elements.[13]

Quite unexpectedly, however, a mathematical and geophysical treatise by F. A. Vening Meinesz seems to throw

[13] I would like to elucidate a few remaining points. The hypothesis to which we referred above is based on the assumption that a continuous sialic layer, which was originally enveloped by a thin layer of water, extended over the entire world. Oceanic basins with a steadily increasing volume of water originated *ipso facto* as the continental blocks were created. It would, consequently, be wrong to presume that the continents emerged from the deep sea and that we might therefore expect to find the continents covered by a veneer of deep-sea sediments. On the contrary, deep-sea deposits are known to be almost nonexistent in the present continents. Yet this cannot be said to conflict with our working hypothesis, the more so as the volume of water has undoubtedly grown since primeval times.

The whole history of geosynclines and folded chains since the pre-Cambrian took place on a basement which had already been folded during the pre-Cambrian. It is impossible to describe the subcrustal processes which were responsible for the distribution and sequence of folding of the continents. It is evident, however, that a repeated buckling of continental areas—a process which may possibly also have taken place in the pre-Cambrian—must have caused the lower side of the continents to become extremely irregular. This feature is, in fact, corroborated by both seismic data and the different altitudes of the mountain belts, which are more or less in a state of isostatic equilibrium.

some light on this side of the problem.[14] In 1944 he published a preliminary paper on the distribution of continents and oceans. The main line of his argumentation runs as follows: It is supposed that a system of convection currents must have come into existence during the primordial phase of cooling of the earth. One possibility is that the rising currents carried sialic components to the surface, where these acid constituents become arranged in a very peculiar manner, viz., in such a way that the breadth of a current is double its height. Admitting that the terrestrial system, at least in a primordial stage of cooling, reached down to a depth of 2,900 km., Meinesz found as their most probable distribution: eight currents, four rising ones alternating with four descending currents. Hence, each current ought to occupy an octant of the outer parts of the globe,

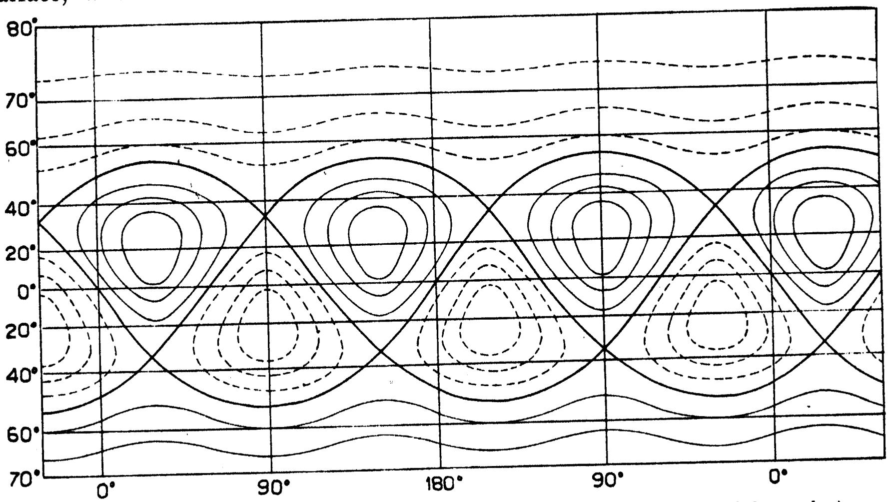

FIG. 4.—Distribution of convection currents during the primordial phase of cooling of the earth. Areas of rising currents are indicated by full-drawn lines; areas of descending currents, by dotted lines (afterMeinesz).

solidified *in loco*, no further displacements taking place on the surface. It fails, therefore, to explain the well-known characteristic differences between the floor of the Atlantic and Indian oceans and the bottom of the Pacific. Another possibility is based on our above-mentioned theory of an original continuous layer of sial enveloping the whole world. There the sialic layer was thought to have been thrust together by the action of subcrustal convection currents. Then Meinesz tried to prove that the system of convection currents had to and it seems plausible to suppose that the axis of two of these octants coincided with the rotation-axis of the earth. The resulting distribution is shown by Figure 4 in Mercator projection. This remarkable result suddenly seems to make clear how the antipodal distribution and the triangular shape of the major terrestrial elements possibly came into being. For the figure clearly shows how these features are graphically represented in the scheme as a necessary result of the mathematical formulas.

Future investigations will undoubtedly bring more unexpected data and still other theoretical points of view.

[14] "De Verdeeling der Continenten en Oceanen over het Aardoppervlak," *Versl. Nederl. Akad. v. W.*, Vol. LIII (1944), pp. 151–59.

PREGLACIAL EROSION SURFACES IN ILLINOIS[1]

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ABSTRACT

A generalized map of buried erosion surfaces in Illinois, compiled from detailed maps of the bedrock topography, provides regional perspective for recognition and correlation of erosion surfaces within the state. A correlation of the Lancaster peneplain of northwestern Illinois, the Calhoun peneplain of western Illinois, and the Ozark peneplain of northern Illinois is suggested; an independent lower surface which developed on the weak rocks of the Illinois basin is described and named the "Central Illinois peneplain"; and possible straths along major preglacial valleys are recognized and named the "Havana strath."

INTRODUCTION

Because of the cover of glacial drift, studies of erosion surfaces in the Mississippi Valley region have been restricted largely to the Driftless Area and to the uplands lying outside the limits of glaciation. Studies in Illinois, which concern (1) the Driftless Area of northwestern Illinois, (2) Calhoun County in western Illinois, and (3) the southern unglaciated section, are summarized briefly in the following pages. A few attempts have been made to correlate buried bedrock uplands in local areas within the glaciated region, but there has been no regional treatment of the problem. In the present study a groundwork for regional interpretation was provided by a detailed bedrock-surface map of Illinois, which was compiled in connection with ground-water studies. A generalized contour map of the erosion surfaces (Fig. 1) summarizes the essential features revealed by the detailed map.

The detailed bedrock-surface map was compiled from about 60,000 records of borings within the state and from all available data on the location of bedrock exposures. In areas where the drift is thin, the present topography, shown by topographic maps, revealed the major features of the bedrock surface. The original maps for about half the state were compiled on topographic sheets and contoured with intervals of 10, 20, and 25 feet. For the remainder of the state, where less control was available, 50-foot contours were drawn on a base map having a scale of 4 miles to the inch. The final map of the entire state was drafted on the latter scale.

The generalized map of the erosion surfaces was drawn from the detailed map by connecting points of equal elevation on interstream areas. It thus shows the general form of the uplands before dissection and could be considered an attempted reconstruction of a late Tertiary land surface somewhat modified by later fluvial and glacial erosion. The element of personal judgment enters into the selection of broad valleys that are to be shown or eliminated, otherwise the contours are closely controlled by numerous points on the divides. This method applied to the upland terraces of southern New England was found to show the same major features as those revealed by multiple projected profiles of the same area.[2]

[1] Published with the permission of the chief of the Illinois Geological Survey, Urbana, Illinois.

[2] George F. Adams, "Upland Terraces in Southern New England," *Jour. Geol.*, Vol. LIII (1945), p. 309.

PREVIOUS STUDIES OF EROSION SURFACES IN ADJOINING DRIFTLESS AREAS

NORTHWESTERN ILLINOIS

The upland surfaces in the Driftless Area of the upper Mississippi Valley have been studied intensively for the last fifty years and are better known than other erosion surfaces in the interior of the continent.[3] Yet there is no general agreement as to the number of cyclical surfaces present or their age. Interpretations have ranged from noncyclical development during a single period of erosion[4] to recognition of five distinct cyclical surfaces.[5] Most writers have identified remnants of either one or two peneplains.

In the Illinois section of the Driftless Area two prominent upland surfaces are present. The upper surface, termed the "Dodgeville peneplain,"[6] is represented by the tops of narrow ridges and isolated mounds capped by Silurian dolomite which are 1,000–1,150 feet above sea-level and 350–450 feet above drainage. The lower surface, called the "Lancaster peneplain,"[7] lies about 200 feet below the Dodgeville plain and is of greater extent than the older surface. It coincides closely with the top of the Ordovician Galena dolomite and slopes southwestward from about 950–800 feet above sea-level (Figs. 3 and 4).[8]

Gravels of the Windrow formation are found on remnants of the Dodgeville peneplain in adjoining states,[9] but only scattered pebbles, occurring at various elevations, have been found in Illinois.[10] Nebraskan drift is reported to be present on both upland surfaces in Iowa but has not been discovered in valleys eroded below the Lancaster plain. This relation led Trowbridge[11] to conclude that the lower surface was undissected at the

[3] O. H. Hershey, "Preglacial Erosion Cycles in Northwestern Illinois," *Amer. Geol.*, Vol. XVIII (1896), pp. 72–100, and "The Physiographic development of the Upper Mississippi Valley," *ibid.*, Vol. XX (1897), pp. 246–68; U. S. Grant and E. E. Burchard, "Lancaster–Mineral Point Folio, Wisconsin-Iowa-Illinois," *U.S. Geol. Surv. Geol. Atlas, Folio 145* (1907), p. 2; A. C. Trowbridge, "Some Partly Dissected Plains in Jo Daviess County, Illinois," *Jour. Geol.*, Vol. XXI (1913), pp. 731–42; E. W. Shaw and A. C. Trowbridge, "Galena-Elizabeth Folio, Illinois-Iowa," *U.S. Geol. Surv. Geol. Atlas, Folio 200* (1916), pp. 9–10; A. C. Trowbridge and E. W. Shaw, "Geology and Geography of the Galena and Elizabeth Quadrangles," *Ill. Geol. Surv. Bull. 26* (1916), pp. 136–46; U. B. Hughes, "A Correlation of the Peneplains of the Driftless Area," *Proc. Iowa Acad. Sci.*, Vol. XXIII (1916), pp. 125–32; A. C. Trowbridge, "The Erosional History of the Driftless Area," *Iowa Univ. Studies*, 1st ser., No. 40 ("Studies in Nat. Hist.," Vol. IX, No. 3 [1921]), pp. 55–127 (the most detailed study of the problem; contains a complete bibliography up to 1921); Lawrence Martin, "Physical Geography of Wisconsin," *Wis. Geol. Surv. Bull. 36* (2d ed., 1932), pp. 69–77; A. C. Trowbridge, in *Kansas Geological Society Guide Book, Ninth Annual Field Conference, Upper Mississippi Valley* (Wichita: Kansas Geological Soc., 1935), pp. 62, 75; F. T. Thwaites, in *Kansas Geological Society Guide Book . . . .*, pp. 105–26; R. E. Bates, "Geomorphic History of the Kickapoo Region, Wisconsin," *Bull. Geol. Soc. Amer.*, Vol. L (1939), pp. 820–41.

[4] Martin, ftn. 3.

[5] Hershey, ftn. 3.

[6] Named from the upland near Dodgeville, Wisconsin, by Trowbridge (p. 64 of ftn. 3 [1921]). Trowbridge now regards the Dodgeville plain as part of the lower Lancaster peneplain rather than as an independent erosion surface (personal communication [1946]).

[7] Named from Lancaster, Wisconsin, by Grant and Burchard, p. 2 of ftn. 3.

[8] Both surfaces are well shown on the Galena and Elizabeth quadrangle maps.

[9] R. D. Salisbury, "Preglacial Gravels on the Quartzite Range near Baraboo, Wisconsin," *Jour. Geol.*, Vol. III (1895), pp. 665–67; Trowbridge, pp. 111–13 of ftn. 3 (1921); F. T. Thwaites and W. H. Twenhofel, "Windrow Formation: An Upland Gravel Formation of the Driftless and Adjacent Areas of the Upper Mississippi Valley," *Bull. Geol. Soc. Amer.*, Vol. XXXII (1920), pp. 293–314.

[10] Trowbridge, p. 112 of ftn. 3 (1921); H. B. Willman, personal communication (1946).

[11] Pp. 123–25 of ftn. 3 (1921) and pp. 62, 75 of ftn. 3 (1935).

time of Nebraskan glaciation. However, the possibility of subsequent removal of the drift from the valleys cannot be eliminated altogether, and the surface may have been dissected at an earlier date. This alternative is indicated by the occurrence of Kansan and possibly Nebraskan drift within deep bedrock valleys of the ancient Mississippi and its tributaries (Fig. 5) in the central part of the state.[12] A compromise view that the deep valley of the ancient Mississippi in the Driftless Area is younger than the deep valley to the south has not been supported by preliminary subsurface studies in the intervening area.

CALHOUN COUNTY, WESTERN ILLINOIS

The narrow upland peninsula between the Mississippi and the Illinois rivers above their junction in western Illinois is driftless except for loess deposits, and two erosion surfaces in the area have been described by W. W. Rubey.[13] An upper surface, forming the crest of the upland at an elevation of 700–750 feet, was named the "Calhoun peneplain," and an intermediate level, 125–250 feet lower, was described as a postmature surface (Fig. 1). The Lincoln Hills, in the adjoining area in Missouri, rise 100–200 feet above the higher surface. The higher surface is largely on Osage (Mississippian) limestones, and to the north it bevels structure. Gravels of "Lafayette type," composed of chert, quartz, and quartzite in a ferruginous matrix, are present on the upper surface north of the Cap au Grés faulted flexure and on a lower upland about 600 feet above sea-level south of the flexure in the southern tip of the county (Fig. 1).[14] This relation raises the question of whether there was important movement along the Cap au Grés fault after deposition of the gravels, as concluded by Rubey,[15] or whether gravels, possibly of different age, were deposited on two distinct surfaces.

SOUTHERN ILLINOIS

The driftless section of southern Illinois roughly includes the area lying south of the Pennsylvanian (Caseyville) escarpment, which extends east-west completely across the southern tip of the state (Fig. 1). Within this region there are two important uplands which are structurally and topographically distinct: (1) the Shawnee section, which includes the Pennsylvanian cuesta and adjoining lower surfaces on the south, and (2) an isolated segment of the Salem plateau of the Ozark region margining the Mississippi trench along the west side of the area.[16] The upland surfaces in the Shawnee section occur at several levels, on various bedrock formations which have been extensively faulted and probably include undifferentiated cyclical and structural surfaces. The uplands of the Salem plateau, in contrast, rise to accordant levels about 700 feet above sea-level and are underlain almost exclusively by deeply weathered Devonian cherts.

No detailed studies have been made of the entire district, and attempted cor-

[12] Leland Horberg, "A Major Buried Valley in East-central Illinois and Its Regional Relationships," *Jour. Geol.*, Vol. LIII (1945), pp. 353–55; unpublished sample study records in the files of the Illinois Geological Survey.

[13] "Geology and Mineral Resource of the Hardin-Brussels Quadrangles, Illinois," unpublished manuscript (1931).

[14] Rubey, ftn. 13; R. D. Salisbury, "On the Northward and Eastward Extension of the Pre-Pleistocene Gravels of the Mississippi Basin," *Bull. Geol. Soc. Amer.*, Vol. III (1892), pp. 183–86; Stuart Weller, "Notes on the Geology of Northern Calhoun County," *Ill. Geol. Surv. Bull. 4* (1907), p. 231.

[15] Ftn. 13.

[16] N. M. Fenneman, *Physiography of Eastern United States* (New York: McGraw-Hill Book Co., Inc.. 1938), pp. 438–39, 651–52, Pl. VI.

relation must be based on studies of two local areas and on broad regional relations. As the result of studies by R. D. Salisbury[17] in Hardin County at the eastern edge of the Shawnee Hills, and by J. E. Lamar[18] in the Carbondale quadrangle in the western part, four erosion surfaces ranging in elevation from 500 to 900 feet have been described, as shown by Table 1. The surface 700–760 feet above sea-level, described by Lamar, appears to be most extensive, and it is probably this surface which R. F. Flint[19] recognized as part of the domed Ozark peneplain and correlated with the Highland Rim surface in Kentucky and Tennessee, and which N. M. Feneman,[20] in addition, correlated with the Lexington peneplain of Kentucky and the Lancaster peneplain in the Driftless Area. The surface is believed by Flint[21] to transect Wilcox (Eocene) strata and therefore to have been completed sometime during the Tertiary. It is significant that the Devonian formations of the Salem Plateau have been weathered and leached to depths of about 400 feet and that this unusual depth of alteration has been ascribed by J. M. Weller[22] to a possible prolonged alteration under peneplain conditions.

TABLE 1

EROSION SURFACES IN SOUTHERN ILLINOIS

Hardin County (Salisbury)		Carbondale Quadrangle (Lamar)	
Name	Elev.	Elev.	Name
Present flood plains	320–340	320–350	Present flood plains
Elizabethtown plain	400–420		
McFarlan plain	500–540	500–560	McFarlan plain(?)
Karbers Ridge plain	600–640	600–650	Karbers Ridge plain(?)
		700–760	Unnamed
Buzzards Point plain	860–900	800–860	Buzzards Point plain(?)

The generalized contour map of the upland surfaces (Fig. 1) suggests (1) the presence of a widespread surface about 700 feet above sea-level that is correlative with the Ozark peneplain, and (2) restricted higher-summit areas which may represent remnants of the Buzzards Point plain or monadnocks on the lower surface. Lower surfaces, 500–550 feet and 600–650 feet in elevation, in the central part of the area may represent the McFarlan and Karbers Ridge plains, respectively, or they may be primarily structural plains.

Lafayette-type gravel occurs on the Salem Plateau in Union County,[23] on the Pennsylvanian escarpment in Gallatin County,[24] and on the crests of hills

[17] Stuart Weller, Charles Butts, L. W. Currier, and R. D. Salisbury, "Geology of Hardin County," *Ill. Geol. Surv. Bull. 41* (1920), pp. 47–52.

[18] "Geology and Mineral Resources of the Carbondale Quadrangle," *Ill. Geol. Surv. Bull. 48* (1925), pp. 152–54.

[19] "Ozark Segment of Mississippi River," *Jour. Geol.*, Vol. XLIX (1941), pp. 634–36, 640.

[20] Pp. 441, 504, and 660 of ftn. 16.

[21] Pp. 639–40 of ftn. 19.

[22] "Devonian System in Southern Illinois," *Ill. Geol. Surv. Bull 68A: Devonian Symposium* (1944), pp. 101–2.

[23] J. M. Weller, personal communication (1945).

[24] Charles Butts, "Geology and Mineral Resources of the Equality-Shawneetown Area," *Ill. Geol. Surv. Bull. 47* (1925), p. 52.

and ridges at lower elevations south to the Ohio valley (Fig. 1). Because of the presence of a weathered zone up to 6 feet thick on the Lafayette and below the loess, J. M. Weller[25] has concluded that deposition of Lafayette gravels was followed by a long period of stable conditions, under which weathering progressed, and that the major period of bedrock erosion giving rise to the present topography occurred during the final part of the post-Lafayette preglacial interval.

BURIED EROSION SURFACES

GALENA UPLAND SURFACE

Description.—The summit areas of the preglacial Galena upland in north-central and northwestern Illinois form a remarkably uniform plain, which slopes southeastward from 950 feet above sea-level at the edge of the Driftless Area to about 800 feet at the south edge of the upland (Lancaster peneplain, Fig. 1). The gradient is about 3 feet per mile, and local relief on the restored surface in most places is less than 50 feet. A broad, upland crest, which extends southeastward across the southwestern part of the upland, coincides closely with the preglacial divide between the ancient Mississippi and Rock River drainage systems (Fig. 5). Along the south and east margin of the upland there is a break in upland profiles between elevations of 800 feet on the north and 650 feet on the south. The zone along which the change occurs is about 20 miles wide and is independent of structure. Along it is drawn the boundary between the Lancaster and Central Illinois peneplains (Fig. 1).

Relation to structure.—The upland plain is developed largely on the Galena dolomite, although in only a few places does it coincide closely with the upper part of the formation. Comparison of the generalized bedrock-surface contours with structure contours of similar interval on the top of the Galena (Figs. 1 and 2) shows that in the western half of the upland the rock surface is generally 150 feet or more below the top of the dolomite, and that to the east the surface crosses onto the overlying Maquoketa shale and lies 100 feet or more above the top of the Galena dolomite. In various local areas the surface is eroded on beds ranging in age from Silurian (Niagaran dolomite) to Cambrian (Trempealeau dolomite).

When the structural and topographic trends are compared, a further lack of coincidence is revealed. The regional slope of the upland is roughly S. 30° E., whereas the three major structural trends are north-south along the Wisconsin arch, east-west along the Savanna-Sabula anticline, and N. 60° W. along the positive element between the Sandwich fault zone and the LaSalle anticline (Fig. 2). Locally there are several places where beveling of structure is indicated: (1) across the Savanna-Sabula anticline and the syncline to the north, (2) across the northwest flank of the LaSalle anticline near its juncture with the Savanna-Sabula anticline in southwestern Ogle County (3) across the northern end of the Sandwich fault zone and related structures in southeastern Ogle and northeastern Lee counties, and (4) across numerous minor folds which plunge down regional dip on the east flank of the Wisconsin arch.

It is concluded that there is only a gross relation between structure and the upland surface and that, in detail, the transgressions of structure are so numerous and important that the surface can-

[25] "Geology and Oil Possibilities of Extreme Southern Illinois," *Ill. Geol. Surv. Rept. Investigations 71* (1940), p. 4?.

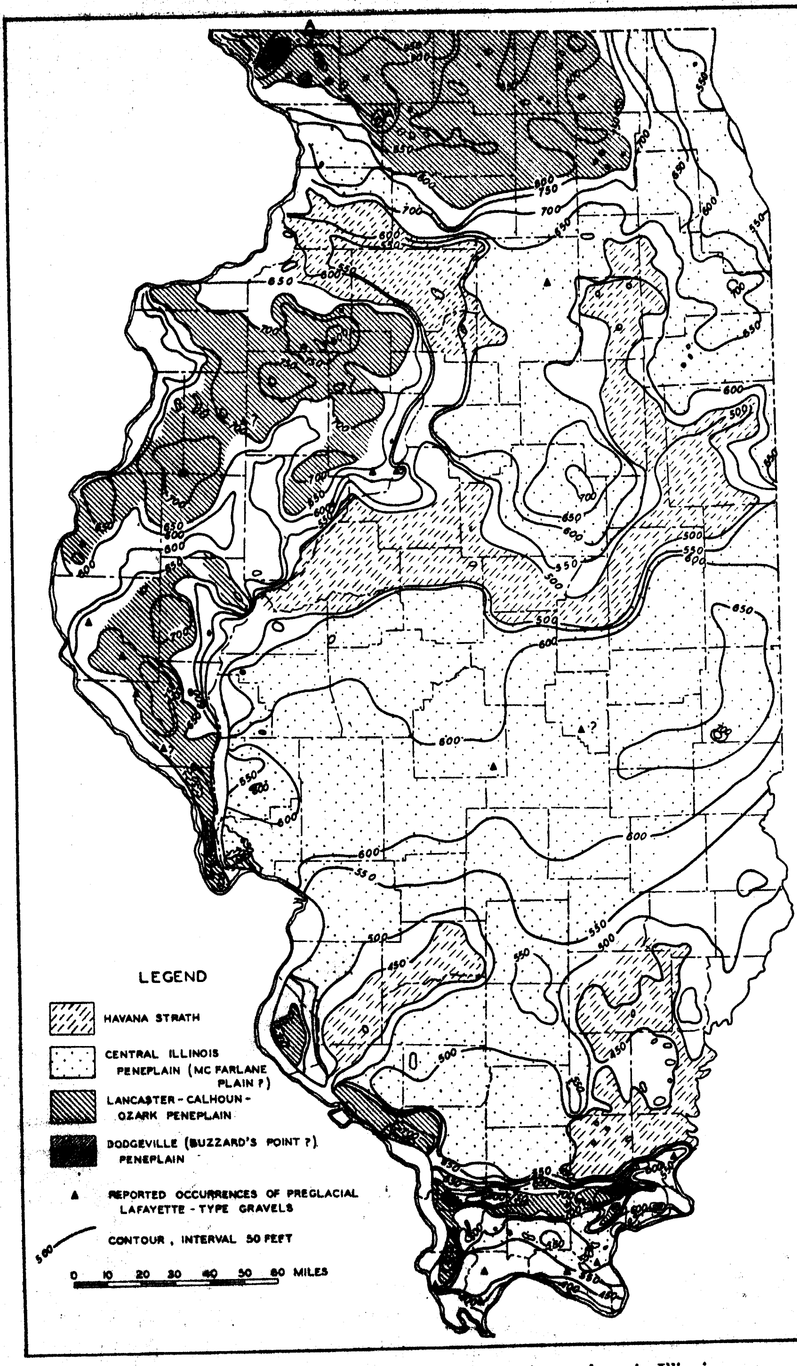

FIG. 1.—Generalized contour map of the erosion surfaces in Illinois

not be considered a simple structure plain.

Correlation.—The Galena upland plain within the drift-covered area was recognized previously[26] and interpreted as modified remnants of what is now generally regarded as the Lancaster or late Tertiary peneplain. This conclusion is substantiated by the present study.

The alternative—that the surface represents the higher Dodgeville peneplain—is possible if downwarping is postulated; and it is supported indirectly by Bates,[27] who concluded from a study of projected profiles in the Driftless Area that the Lancaster peneplain of Trowbridge is a stripped structural plain rather than a cyclical surface. This conclusion appears to be justified by relations in the Illinois section of the Driftless Area, where the Lancaster peneplain coincides closely with the top of the Galena dolomite. However, if it is the Lancaster surface that extends southeastward below the drift and bevels structure on the Galena upland, the cyclical origin of the surface finds new support. In fact, one of the strongest evidences of beveling is found just south of the drift margin, where the Maquoketa shale and Silurian dolomite along the syncline north of the Savanna-Sabula anticline are truncated by the bedrock surface (Fig. 3).

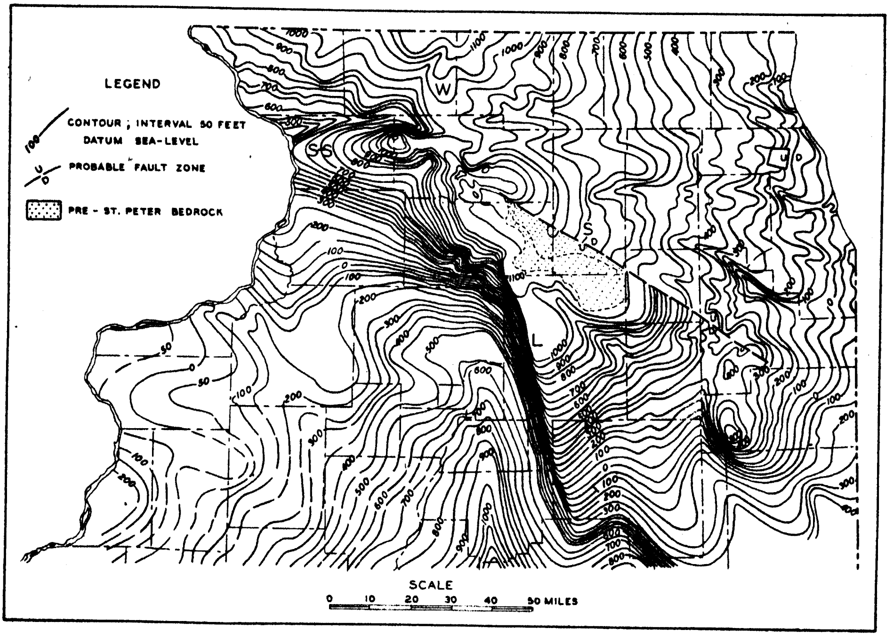

FIG. 2.—Structure contours on top of the Galena dolomite in northern Illinois. *W*, Wisconsin arch; *S-S*, Savanna-Sabula anticline; *S*, Sandwich fault zone; *L*, LaSalle anticline.

[26] Hershey ftn. 3 (1896) (1897); J H. Bretz, "Geology and Mineral Resources of the Kings Quadrangle," *Ill. Geol. Surv. Bull. 43* (1923), pp. 273–77; R. S. Knappen, "Geology and Mineral Resources of the Dixon Quadrangle," *Ill. Geol. Surv. Bull. 49* (1926), pp. 90–93.

[27] Pp. 833–37 of ftn. 3.

In an attempt to determine whether this bedrock surface represents the Lancaster or the Dodgeville surface, a generalized contour map covering most of the Driftless Area in Illinois was constructed from topographic sheets (Fig. 4). The reconstruction indicates (1) that the Dodgeville upland in its northern part is delimited from Lancaster surfaces to the east and west by clearly defined escarpments but that to the south there is no sharp break to a lower surface; (2) that possible isolated remnants of the Dodgeville peneplain in the south half of the Elizabeth quadrangle are distinct from the Lancaster surface on the north but descend more gradually to a lower surface on the south; (3) that the Lancaster surface in the northern half of the Elizabeth quadrangle continues eastward below the drift and possibly southward onto the uplands of the Savanna quadrangle. Relations 1 and 2 suggest the possibility that the Dodgeville peneplain is downwarped to the south and that the Lancaster could be a local southwest-sloping structural plain. However, it appears to be the Lancaster surface which continues eastward into the area where the buried Galena upland surface is best developed (Fig. 1). Because of this, the Galena upland surface is correlated with the Lancaster peneplain.

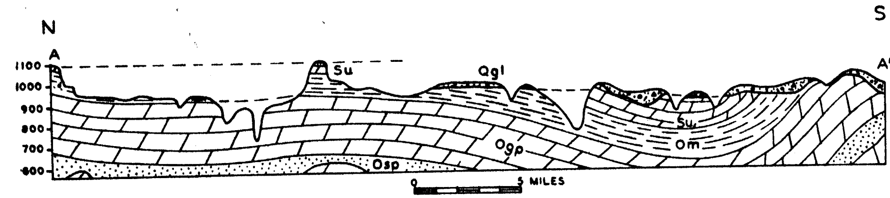

FIG. 3.—Cross-section showing Dodgeville (*upper*) and Lancaster (*lower*) surfaces in northwestern Illinois along *A–A'* of Fig. 1. *Qgl*, glacial drift; *Su*, Silurian dolomite; *Om*, Maquoketa shale; *Ogp*, Galena-Platteville dolomite; *Osp*, St. Peter sandstone.

UPLAND SURFACES IN WESTERN ILLINOIS

Description.—The bedrock uplands in western Illinois are less continuous and more variable in elevation than those of the Galena upland to the north and the Pennsylvanian lowland to the east. They appear to represent a broad, mature surface, on which there are possible remnants of a summit peneplain 700–800 feet above sea-level and possibly a lower surface 600–650 feet above sea-level (Fig. 1). The upper surface is interrupted by two broad valleys, so that it is not continuous from north to south. Possible remnants of the lower surface are present only along the northern and eastern margin of the upland.

In the western part of the area the upper surface is continuous from weak Pennsylvanian beds on the east to resistant Mississippian (Meramec and Osage) dolomites to the west. Actually, the highest elevations are on Pennsylvanian strata near the northwest corner of the upland. The high elevation of the upland as a whole compared with the lowland to the east cannot be explained by differential erosion, as there are no important differences in the compositon of the Pennsylvanian rocks in the two areas. Nor is there any marked difference in drainage position, since the higher upland is essentially surrounded by major preglacial valleys. One possible explana-

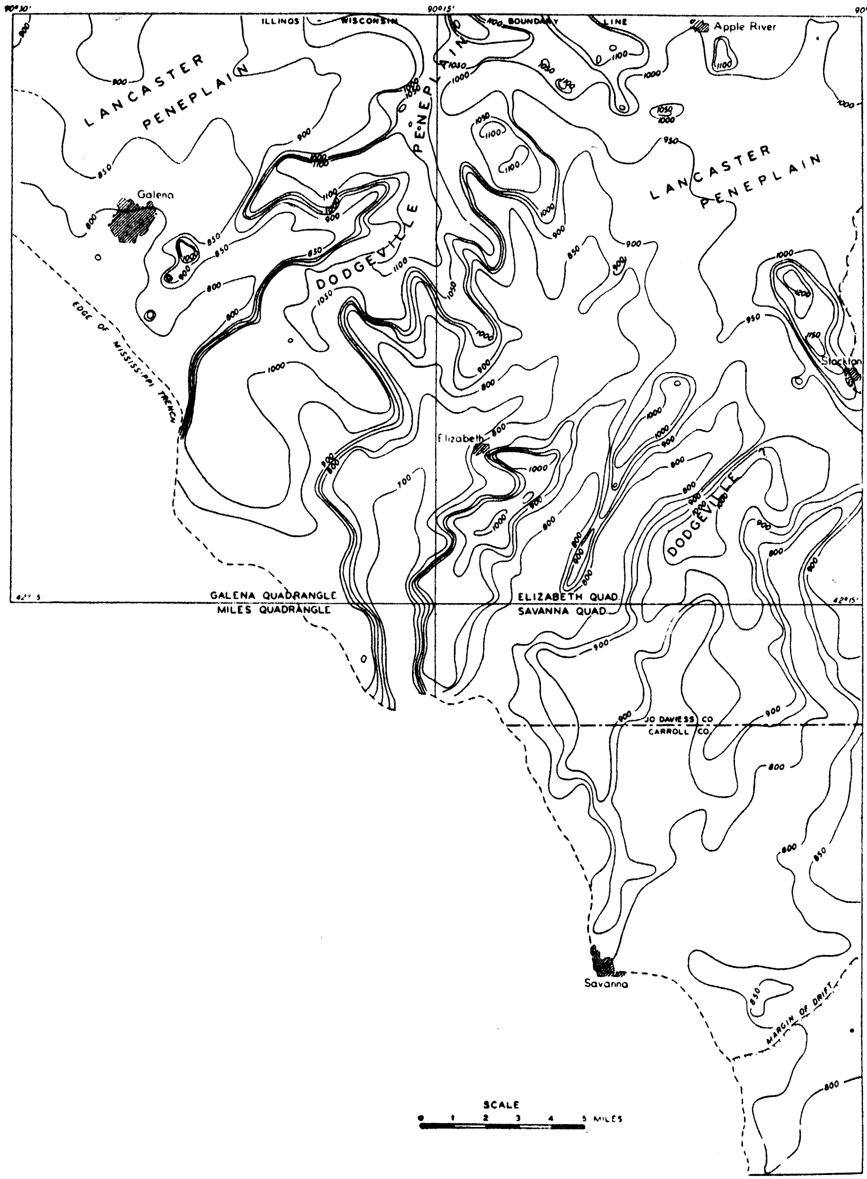

FIG. 4.—Generalized contour map of upland surfaces in the Driftless Area, northwestern Illinois

tion may be found in the higher structural position and diminished thickness of the Pennsylvanian strata to the west, so that resistant Mississippian limestones floor the lower portions of many large bedrock valleys. The local baselevels provided by these resistant beds may have been effective in retarding erosion of the uplands. This explanation, however, would not apply to the northern third of the upland, where Mississippian beds are absent, nor would it explain why erosion of the lower surface to the east was not also retarded by similar local baselevels along its western margin. For these reasons it is believed that structural control was not a major factor and that the escarpment between the two areas represents the junction of a higher and a lower peneplain.

Preglacial gravels of Lafayette type have been reported from Pike, Adams, Hancock, Fulton, Peoria, Tazewell, Warren, Henderson, and possibly Rock Island counties (Fig. 1).[28]

Correlation.—Summit areas in the southern part of the upland are continuous with the Calhoun peneplain of the driftless area of western Illinois described by Rubey[29] and those in the northern part are close to the required level. If the surface is projected northward across the Green River bedrock lowland, which separates the uplands of western Illinois from the Galena upland (Fig. 1), a correlation with the Lancaster peneplain is possible. Lower surfaces along the eastern and northern margins of the upland are probably extensions of the Central Illinois peneplain from the preglacial Pennsylvanian lowland to the east.

UPLAND SURFACE IN SOUTHWESTERN ILLINOIS

Description.—The bedrock upland northwest of the southern Illinois driftless area in Monroe, Randolph, and Jackson counties is covered by relatively thin drift and forms a prominent feature of the present topography (Fig. 1). A central ridge which rises to a maximum elevation of over 700 feet extends along the length of the upland and is bordered by extensive flattish summit areas. The summit areas have a general elevation of 600–700 feet north of Kaskaskia bedrock valley and 600–650 feet south of the valley. The upland is underlain by Mississippian (Osage, Meramec and Chester) strata and represents a segment of the Salem plateau of the Ozarks isolated by the Mississippi River.

Correlation.—The upland was considered a part of the Ozark topographic dome by R. F. Flint,[30] and on the basis of projected profiles was interpreted as an upwarped peneplain. It thus forms a northward continuation of the Ozark peneplain from the driftless area to the south. Northwestward, the surface appears to continue across the Mississippi River into the St. Louis area[31] and to merge with the Calhoun peneplain of western Illinois.

[28] A. H. Worthen, "Geology of Hancock County," *Geol. Surv. of Ill.*, Vol. I (1866), p. 330; "Geology of Pike County," *ibid.*, Vol. IV (1870), p. 37; "Geology of Fulton County," *ibid.*, p. 91; H. M. Bannister, "Geology of Tazewell, McLean, Logan, and Menard Counties," *Geol. Surv. of Ill.*, Vol. IV (1870), p. 179. Occurrences in Adams, Henderson, and possibly Rock Island county are reported by R. D. Salisbury in "A Further Note on the Ages of the Orange Sands," *Amer. Jour. Sci.*, Vol. XLII (3d ser., 1891), pp. 252–53, and in ftn. 14. The occurrence in Peoria County was noted by J. A. Udden in "The Geology and Mineral Resources of the Peoria Quadrangle," *U.S. Geol. Surv. Bull. 506* (1912), p. 50, and possible occurrences in southern Pike and eastern Warren counties were reported by J. E. Lamar (personal communication [1945]).

[29] Ftn. 13.

[30] Pp. 634–36 of ftn. 19.

[31] N. M. Fenneman, "Physiography of the St. Louis Area," *Ill. Geol. Surv. Bull 12* (1909), pp. 52, 57; "Geology and Mineral Resources of the St. Louis Quadrangle, Missouri-Illinois," *U.S. Geol. Surv. Bull. 438* (1911), pp. 43–44.

CENTRAL ILLINOIS PENEPLAIN

Description.—This modified surface is believed to extend over most of the Pennsylvanian lowland and to be widely developed on the Niagara cuesta of northeastern Illinois. It is thus considered the most extensive erosion surface within the state. The surface is unusually uniform in elevation; and, throughout the northern three-quarters of the area, upland elevations in most places lie between the 600- and the 650-foot contours; to the south they descend to about 500 feet (Fig. 1). The highest sections of the upland rise about 100 feet above the general level in the east-central part of the state and form broad crests which conform closely to preglacial drainage divides (Figs. 1 and 5). Small remnants of the surface may be present in the Pennsylvanian upland to the west, as previously noted, and also southwest of the Galena upland in northwestern Illinois.

There is a general coincidence of the surface with the Illinois structural basin, but a general lack of adjustment to local structures. Transection of structure is especially apparent along the LaSalle uplift, which extends northwest-southeast across the northern half of the area (Fig. 2). In the LaSalle region, beds ranging in age from Pennsylvanian to Ordovician (Shakopee dolomite) are beveled by the surface. Further lack of adjustment to structure is indicated by the possible extension of the surface onto the hard rocks of the Niagara cuesta of northeastern Illinois.

Three possible occurrences of preglacial Lafayette-type gravel are known within the area (Fig. 1): (1) on the bedrock upland at Pana, in Christian County, where a thin bed of ferruginous conglomerate with angular and rounded chert pebbles was penetrated at the base of the drift in a diamond-drill boring;[32] (2) near Sullivan, about 30 miles northeast in central Moultrie County, where about 15 feet of ferruginous conglomerate with quartz and chert pebbles, mixed with weathered Pennsylvanian siltstone at the base of the drift, were identified by the writer from well sample cuttings; and (3) near Wedron, in LaSalle County, in the northern part of the area, where 2–4 feet of limonitic conglomerate and sandstone with polished chert pebbles directly overlies the bedrock.[33] The two latter deposits occur below the highest part of the upland at elevations of about 485 and 550 feet, respectively, and may be reworked from a former extensive upland gravel.

Correlation.—The surface is believed to represent a single peneplain developed largely on the weak rocks of the Illinois basin below the level of older erosion surfaces to the north, west, and south. The surface was recognized previously in various parts of southern Illinois[34] and in most cases was ascribed to a "third cycle" of erosion, completed in the Tertiary, following the two cycles represented by upland plains in the driftless areas of southern and northwestern Illinois.[35] In the northern part of the area

[32] Frank Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Surv. Mono. 38* (1899), p. 107.

[33] H. B. Willman and J. N. Payne, "Geology and Mineral Resources of the Marseilles, Ottawa, and Streator Quadrangles," *Ill. Geol. Surv. Bull. 66* (1942), pp. 204–5.

[34] E. W. Shaw and T. E. Savage, "Murphysboro-Herrin Folio, Illinois," *U.S. Geol. Surv. Atlas, Folio 185* (1912), p. 12, and "Tallula-Springfield Folio, Illinois," *U.S. Geol. Surv. Atlas, Folio 188* (1913), p. 10; E. W. Shaw, "New Athens-Okawville Folio, Illinois," *U.S. Geol. Surv. Atlas, Folio 213* (1921), p. 8, and "Carlyle-Centralia Folio, Illinois," *U.S. Geol. Surv. Atlas, Folio 216* (1923), p. 7; Wallace Lee, "Gillespie–Mt. Olive Folio, Illinois," *U.S. Geol. Surv. Atlas, Folio 220* (1926), p. 1.

[35] This is the conclusion of E. W. Shaw and T. E. Savage in ftn. 34 (1912), (1913); and Shaw (1921),

the surface has been clearly identified in LaSalle County and correlated with the Galena upland surface and the Dodgeville peneplain.[36] This correlation is not supported by the present study because of the physiographic discontinuity of the LaSalle County surface with the Galena upland plain and the possibility that the latter is continuous with the Lancaster peneplain rather than with the Dodgeville.

STRATHS ALONG MAJOR PREGLACIAL VALLEYS

A broad-valley stage preceding stream entrenchment is evidenced by possible straths along the preglacial Mahomet (Teays), ancient Mississippi, Kaskaskia, and Wabash drainage systems (Figs. 1 and 5). The existence of these surfaces is interpreted entirely from subsurface data, and they are related only indirectly to the alluvial plains which floor some of these valleys at present. The cyclical origin of some of the surfaces is uncertain because local baselevels and glacial changes may have been important factors in their development. Also, in some places the bedrock surface could not be delineated accurately because of insufficient data. It is significant, however, that the cumulative data indicate rock benches, which seem to descend regularly from 550 feet on the north to 450 feet and less toward the south, and that the valleys are much wider than those resulting from late preglacial entrenchment. Because of these features, an erosion level intermediate between the Central Illinois peneplain and the "deep-stage" valleys is postulated. It is named the "Havana strath" from the extensive bedrock lowland near the junction of the Mahomet (Teays) and ancient Mississippi bedrock valleys.

ENTRENCHED PREGLACIAL VALLEYS

The deep-stage valleys (Fig. 5) are entrenched 100 feet or more below the Havana straths and probably represent the final episode in preglacial erosional history. Although the preglacial age of the upper Mississippi bedrock valley may be open to question, there is evidence that Kansan and, possibly, Nebraskan drift is present in bedrock valleys of the ancient Mississippi, Rock, and Mahomet (Teays) systems, indicating that these valleys, and probably most of the deep bedrock valleys, were eroded to their present depths before the glacial period.

SUMMARY OF EROSIONAL HISTORY

The oldest erosion surface in the state may be represented by remnants of the Dodgeville peneplain in northwestern Illinois and the Buzzards Point plain in southern Illinois. Below these levels the Lancaster-Calhoun-Ozark peneplain appears to have developed as an extensive regional surface in late Tertiary time. Following completion of the peneplain, and probably prior to the making of the central Illinois peneplain, Lafayette-type gravels were spread over its surface,[37] and it appears likely that the positions of

(1923). Wallace Lee (pp. 1, 11 of ftn. 34) correlated the surface with the lower (Lancaster) surface in the Driftless Area and suggested its possible completion in the Mesozoic and uplift in the Tertiary.

[36] Willman and Payne, pp. 204–5 of ftn. 33.

[37] These gravels present numerous unsolved problems. Their age is indefinite "Tertiary" and it is probable that similar deposits of various ages are to be found in the upper Mississippi Valley as well as in the Gulf states. Similarities in composition could be explained by the re-working of an originally widespread deposit or by the repeated access to similar source materials. It is uncertain whether the gravels on the Lancaster-Calhoun-Ozark surface are older than the deposits at lower elevations in central and southern Illinois or whether they are essentially contemporaneous and therefore record important deformation of the peneplain.

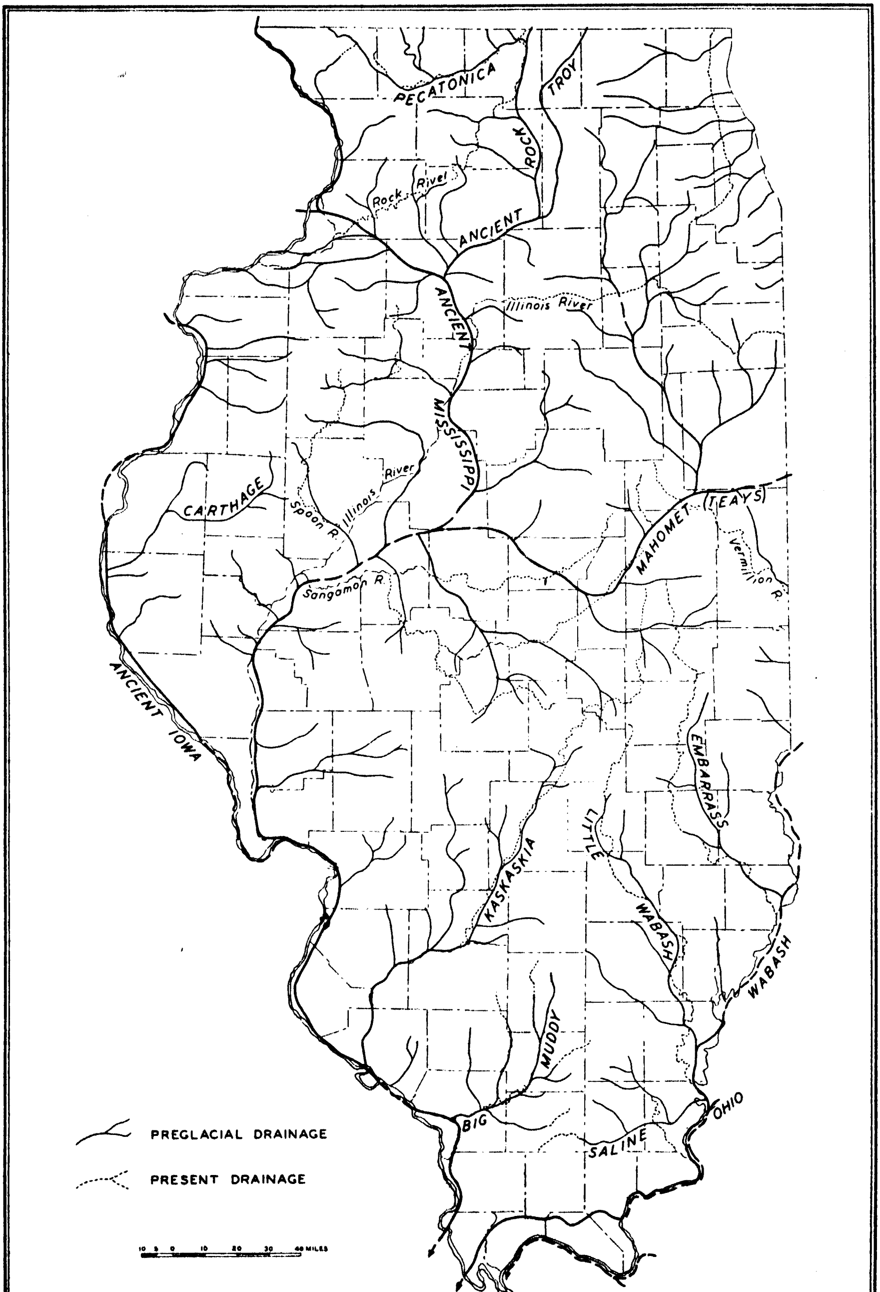

FIG. 5.—Major preglacial drainage systems in Illinois

major preglacial drainage lines were determined. With uplift of the peneplain, the larger streams in many places were established transverse to structure in superimposed valleys or in antecedent valleys on the upwarped peneplain surface. Outstanding transverse valleys in the state include the courses of (1) the ancient Mississippi across the west flank of the Wisconsin arch and Savanna-Sabula anticline in northwestern Illinois, (2) the ancient Rock across the positive element between the Sandwich fault zone and LaSalle anticline in north-central Illinois (Figs. 2 and 5), (3) the ancient Iowa and ancient Mississippi across the Cap au Grés structure in the Calhoun County area of western Illinois, and (4) the ancient Mississippi across the east flank of the Ozark dome in southwestern Illinois.[38]

During the third cycle of erosion which followed, a local peneplain was eroded on the weak beds of the Illinois basin. The extent of the surface to the east and northeast is not known, but to the north and west it is believed to terminate against remnant uplands of the older land surface. The ancestral Mississippi and Mahomet (Teays) were probably the major streams, although their courses may not have been established until the close of the cycle.

During the Havana cycle the main preglacial drainage lines were present and broad valleys were eroded along the ancient Mississippi, Mahomet, Kaskaskia, and Wabash systems. A rejuvenation of drainage initiated the deep-valley stage, which continued until interruption of the cycle by glaciation. This last cycle may have opened with the earth movements at the close of the Tertiary, in which event the main bedrock valleys could have been entrenched during the preglacial Pleistocene.

[38] Considered antecedent to the doming of the Ozark peneplain by R. F. Flint (ftn. 19).

NOTE ON THE GEOLOGY OF AGATTU, AN ALEUTIAN ISLAND

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ABSTRACT

Agattu is unique among the volcanic Aleutian Islands in being composed almost entirely of well-bedded sedimentary rocks. These rocks were clearly deposited in water and are composed chiefly of amorphous silica and fine detritus derived from a volcanic terrain. Igneous rocks are sparsely represented by intrusions of porphyry, diabase, and trap. The entire island has been heavily glaciated.

INTRODUCTION

Agattu lies 30 miles southeast of Attu, the most westerly island of the Aleutian chain, an arc of rugged volcanic islands stretching 1,000 miles across the North Pacific (Fig. 1). Agattu sprang into prominence early in the Aleutian campaign of World War II when Japanese ships anchored off its eastern shore. Actually, the Japs never occupied the island in force.

Agattu is 19 miles long by $10\frac{1}{2}$ miles wide (Fig. 2). It consists of a rolling plateau a few hundred feet above sea-level, with a small range of mountains along the north shore.

The following observations were made incidental to 4 days' military duty on the island in July, 1945. They are of the roughest reconnaissance variety, as there was little time or opportunity for geological work. Only the area between Korab Cove and the east coast was covered on the ground. Supplementary information was obtained from Army Air Force aerial photographs. Lithologic descriptions are based solely on megascopic field examination.

BEDROCK GEOLOGY

GENERAL

Little has been published on the geology of the Aleutians, although they are known to be predominantly volcanic and to include a number of active volcanoes. Stratified deposits, some containing Tertiary plant and invertebrate remains, are reported to crop out sporadically in the Aleutians.[1] However, sedimentary rocks appear to be a minor constituent except on Agattu, 80–90 per cent of which consists of sedimentary beds.

SEDIMENTARY ROCKS

The sedimentary rocks of Agattu are chiefly fine grained, well bedded (Fig. 3), and rich in amorphous silica. Beds of pure chert are not common, but fully 25 per cent of the section consists of impure chert. In addition, most of the fine-grained strata are highly siliceous. Less abundant beds of particles in the medium- to coarse-sand size appear to have been derived from volcanic rocks of basic to intermediate composition. Massive layers of conglomerate containing subangular to subrounded fragments of volcanic rocks up to 3 inches in diameter constitute a small part of the section.

Various shades of gray and green predominate in the Agattu beds, supplemented by cream, brown, and purple. All the rocks are coherent, and the degree of cementation increases with decreasing grain size so that the finest rocks are hard and brittle.

Stratification is uniform and well de-

[1] S. R. Capps, "Notes on the Geology of the Alaska Peninsula and Aleutian Islands," *U.S. Geol. Surv. Bull. 857-D* (1934), pp. 143–44.

veloped, particularly in the fine materials where beds 1–3 inches thick predominate. The fine-grained rocks also show prominent lamination and are cut by a well-developed system of closely spaced fractures.

The Agattu beds are horizontal to gently inclined with dips up to 30 degrees. It seems likely that there are open folds, although none was observed. Strikes along the east coast are a little east of north and dips are east. Aerial photographs suggest a similar strike throughout much of the eastern half of the island. Linear fracture zones, probably faults, cut the sedimentary beds obliquely. Two of the most prominent fracture zones, trending N. 50° E. and N. 65° E., cross the island from Korab Cove to the east coast south of McDonald Cove (Fig. 4).

From exposures observed in sea cliffs, the thickness of these deposits need not exceed 400–500 feet. However, aerial

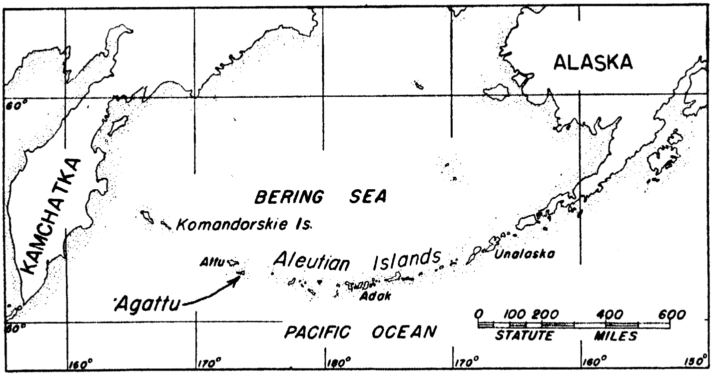

FIG. 1.—North Pacific Region

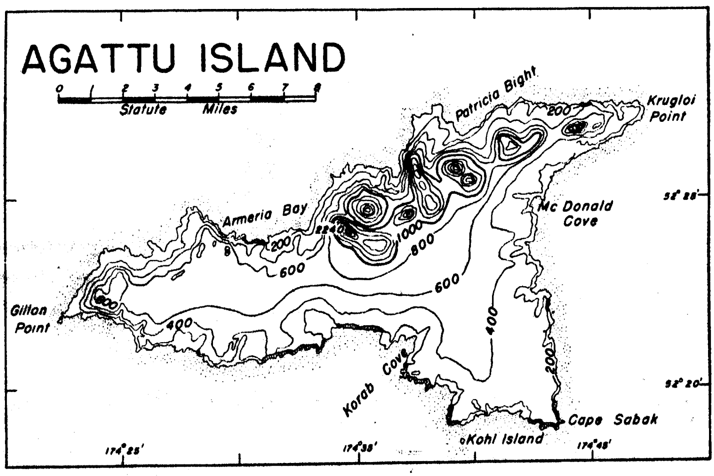

FIG. 2.—Agattu Island

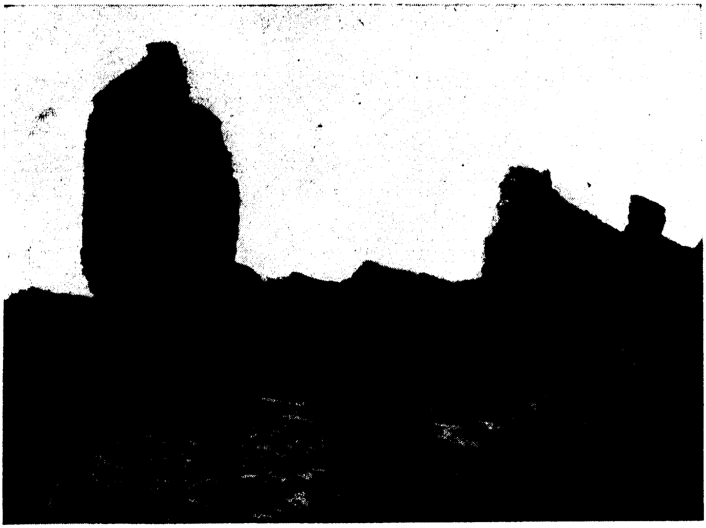

FIG. 3.—Sedimentary beds, east coast of Agattu south of McDonald Cove

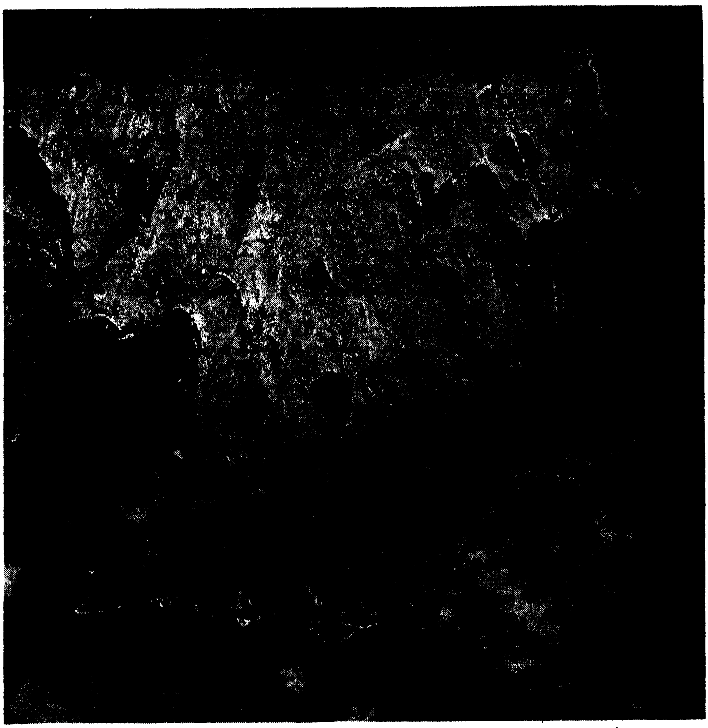

FIG. 4.—Vertical aerial photograph of Agattu Island in vicinity of Korab Cove, taken from 13,000 feet. (Official photograph, U.S. Army Air Forces.)

photographs show that the tops of peaks rising to 2,200 feet in the mountains of the north shore consist of nearly horizontal strata. If these mountains are composed wholly of beds in similar attitude; and it is so suggested by the photographs, the total thickness cannot be much less than 2,000 feet. Sections of inclined beds in the plateau require a similar minimum thickness unless duplicated by undetected faults or folds. It seems safe to state that the Agattu beds are at least 2,000 feet thick.

The bedding, sorting, and uniformity of these strata demonstrate deposition in water; whether fresh or salt is not known. Their composition shows that they were derived from a volcanic terrain, and the large amount of chert may suggest volcanic emanations in or near the basin of deposition.

The nature and origin of the basin in which the Agattu beds accumulated poses problems not solvable with the information available. If the Agattu beds are merely local, they may have been laid down in a great volcanic crater filled with either salt or fresh water. The Komandorskie Islands, 275 miles northwest of Agattu, and the Kamchatka Peninsula, 150 miles farther west (Fig. 1), contain sedimentary rocks.[2] The Komandorskies rest on a submarine ridge forming a northwestward continuation of the Aleutian ridge.[3] If the Agattu beds are related to the rocks exposed in the Komandorskies and Kamchatka, it is possible that sedimentary rocks may be an important constituent of the western Aleutian-Komandorskie ridge. In this case the basin of deposition would have been of considerable extent, and at least a partial diastropic origin of the western Aleutian-Komandorskie ridge is indicated rather than a simple *in situ* accumulation of volcanic rocks.

No fossils were found in the Agattu beds. They could be either Mesozoic or Tertiary. Their induration and lack of resemblance to any of the Tertiary strata on other Aleutian Islands[4] or the Alaska Peninsula[5] may indicate a pre-Tertiary age. They are certainly older than any of the igneous rocks seen on Agattu and resemble some parts of the thick Mesozoic section, particularly the Triassic, of the Alaska Peninsula,[6] although lithologic comparisons have little validity at such a great distance. Conversely the mild deformation of the Agattu beds, their content of volcanic debris, and the report of somewhat similar Tertiary strata on the Komandorskies[7] suggest a Tertiary age. Capps[8] did not see any

[2] G. M. Dawson, "Geological Notes on Some of the Coasts and Islands of Bering Sea and Vicinity," *Bull. Geol. Soc. Amer.*, Vol. V (1894), pp. 124–26, 129–30.

[3] H. W. Murray, "Profiles of the Aleutian Trench," *Bull. Geol. Soc. Amer.*, Vol. LVI (1945), Pl. I, p. 757.

[4] Capps, pp. 143–44 of ftn. 1 (1934); H. B. Collins, A. H. Clark, and E. H. Walker, "The Aleutian Islands," *Smithsonian Inst. War Background Studies No. 21* (1945), p. 6.

[5] W. H. Dall and G. D. Harris, "The Neocene of North America," *U.S. Geol. Surv. Bull. 84* (1892), pp. 242–57; W. W. Atwood, "Geology and Mineral Resources of Parts of the Alaska Peninsula," *U.S. Geol. Surv. Bull. 467* (1911), pp. 49–67; W. R. Smith and A. A. Baker, "The Cold Bay–Chignik District," *U.S. Geol. Surv. Bull. 755* (1924), p. 185; R. S. Knappen, "Geology and Mineral Resources of the Aniakchak District," *U.S. Geol. Surv. Bull. 797* (1929), pp. 195–98; Arthur Hollick, "The Tertiary Floras of Alaska," *U.S. Geol. Surv. Prof. Paper 182* (1936), p. 29.

[6] Atwood, pp. 30–48 of ftn. 5 (1911); P. S. Smith, "Areal Geology of Alaska," *U.S. Geol. Surv. Prof. Paper 192* (1939), pp. 37–38, 44–46, 50–52; S. R. Capps, "The Cold Bay District," *U.S. Geol. Surv. Bull. 739* (1922), pp. 92–105; W. R. Smith, "The Cold Bay–Katmai District," *U.S. Geol. Surv. Bull. 773* (1925), pp. 194–97; Smith and Baker, pp. 171–85 of ftn. 5 (1924).

[7] Dawson, pp. 124–25 of ftn. 2 (1894).

[8] Pp. 143–44 of ftn. 1 (1934).

rocks in the Aleutians that he considered pre-Tertiary, but he did not visit Agattu. Dall and Harris[9] favored a pre-Tertiary age for some Aleutian rocks but without any firm basis. However, the possibility that the Agattu beds may be older than Tertiary should be kept in mind, for a confirmation would indicate that the Aleutian ridge may be built in part of pre-volcanic rocks, as previously suggested.[10]

IGNEOUS ROCKS

In southern Agattu 3 miles east of Korab Cove a body of gray porphyry is exposed. Brief field observation suggests it is a small pluton intruded into the sedimentary beds. The rock contains large phenocrysts of feldspar, up to 1 inch long, and small crystals of hornblende and biotite set in a medium phaneric groundmass. From field examination the rock appears to be approximately a diorite.

On the south coast near Kohl Island is a massive intrusive of diabase rich in magnetite. Kohl Island is composed of the same rock. Aerial photographs suggest that Gillon Point at the western end of the island and Armeria Point on the north shore consist of diabase or similar rock. Diabase and trap dikes, 6 inches to 100 feet wide, cut the sedimentary beds. Most dikes are approximately vertical and strike within 25 degrees of east-west. A few have more northerly trends.

No extrusive rocks were observed on Agattu. The mountain peaks of the north shore have the external appearance of volcanoes but consist largely, if not entirely, of sedimentary beds.

[9] Pp. 244–45 of ftn. 5 (1892).

[10] Dall and Harris, p. 242 of ftn. 5 (1892); T. A. Jaggar, *Volcanoes Declare War* (Honolulu, T.H.: Paradise of the Pacific, Ltd., 1945), pp. 81–82.

GEOMORPHOLOGY

THE LANDSCAPE

Fully two-thirds of Agattu is a low rolling plateau, but along the north shore a small mountain range rises abruptly from the sea. The highest elevation known in these mountains is 2,240 feet. They are highest and most rugged from Krugloi Point to Armeria Bay. Peaks and ridges above 1,000 feet are sharp and angular; below 1,000 feet they are rounded and smoothed. Valleys are wide and U-shaped, and passes crossing the mountains are mostly low, broad, and open. Westward from Armeria Bay hills rise abruptly 700–800 feet from the sea on the north and drop off gently to the plateau on the south. Near Gillon Point these hills give way to a south-sloping plateau at 800–900 feet.

The remainder of Agattu consists of a rolling lake-dotted plateau at 300–500 feet with a relief usually less than 100 feet. Much of this plateau country has a distinct grain trending 10°–30° east of north (Fig. 4). In the eastern half of the island this grain is caused by tilted sedimentary beds, and the ridges are crests of low cuestas. In the western half the grain may be controlled by a well-developed joint system. Ridges held up by dikes and linear depressions along fracture zones cross the grain obliquely. Prominent depressions have been eroded along two major fracture zones extending east of north from Korab Cove. Since the plateau truncates the upturned edges of sedimentary beds, it is clearly an erosion surface, but whether of marine or terrestrial origin is not known.

Lakes are the most prominent feature of the plateau, and Agattu is estimated to have at least 1,000 ponds and lakes (Fig. 4). These water bodies are shallow and mostly less than ½ mile long. They

lie in rock basins, the shape and distribution of which are clearly determined by rock structure in many places (Fig. 4). Lakes lie at all elevations; some occupy basins on the sides and summits of ridges, and others are on valley floors. A number have no surface outlet, but approximately 75 per cent are drained by small streams running from one lake to another and eventually to the sea. Lakes are less abundant in the mountains, but here, too, they occupy rock basins and are scattered more or less haphazardly over the landscape up to about 1,000 feet.

Streams on Agattu are small and flow across the plateau in shallow irregularly winding valleys. Near the sea they plunge into deep, narrow, V-shaped gorges containing cascades and waterfalls. The largest stream on the island flows from some lakes north of Korab Cove eastward 4 miles to McDonald Cove.

The plateau is thinly mantled with soil and angular rock fragments on which grows a tundra mat of moss, grass, and low heath.

Practically the entire shore of the island is bordered by vertical sea cliffs 50–200 feet high. Stacks, arches, and offshore reefs are abundant. The few bouldery, narrow beaches are limited largely to the heads of coves and bays.

GLACIATION

Cirques and U-shaped valleys in the mountains, rounded and grooved bedrock outcrops on the plateau, and the abundant rock-basin lakes all suggest extensive glaciation; but moraines, other deposits of drift, and striated bedrock surfaces have not been seen. However, by comparison with the islands of Attu and Adak, where evidence of glaciation is irrefutable, there can be little doubt that Agattu has been heavily and extensively glaciated.

Ice covered the entire island with the possible exception of the highest peaks and ridges. All areas below 1,000 feet show smoothing, scouring, and excavation. The lack of drift can be attributed to the fact that the ice flowed into the sea on all sides.

The north-shore mountains were presumably the initial gathering area for snow, and the ice streams so nourished flowed down onto the plateau to the south, where they coalesced to form a piedmont glacier. That the plateau ever had a true ice cap with a center of nourishment independent of the mountains is possible but not certain. Judging from the elevation of cirque floors, the size of the ice mass, and evidence of glaciation on near-by low-lying islands, the glacial snowline on Agattu must have been no higher than 800–1,000 feet. The present snowline lies above the highest peak, 2,240 feet, and may be about 3,300 feet in the eastern Aleutians.[11] The ice covering the plateau must have been at least 200–300 feet thick in order to move, scour the bedrock, and excavate the lake basins. Parts of the upper surface of this plateau ice could easily have approached 800 feet and may have been high enough to receive nourishment independently of the mountains. In this way it could have become an independent ice cap.

The raw freshness of the topography, lakes, and rock surfaces indicates the relative recency of the glaciation. However, erosion of sea cliffs and postglacial stream gorges suggests that ice has not covered the entire island since the post-Wisconsin optimum,[12] which started ap-

[11] J. Wascowicz, "Studies on the Snow-Line in Canada and Alaska," *Acad. Polonaise Sci. and Letters, Intern. Bull. Series A* (1929), Fig. 4, p. 395.

[12] The period of warmest and driest climate following the Wisconsin has been called the middle post-Pleistocene optimum, the postglacial optimum, the postglacial climatic optimum, and simply the climatic optimum. R. F. Flint ("Progress and Prob-

proximately 7,500 years ago.[13] Ice almost completely covered Agattu during the late Wisconsin and may have remained on parts of the island well into the post-Wisconsin period. The fact that there are no glaciers on the island today indicates that the ice was completely gone by the culmination of the post-Wisconsin optimum, a warmer, drier period than the present. Unfortunately, field observations were not complete enough to throw any light on the possibility of a rebirth of glaciers following the post-Wisconsin optimum. Present-day glaciers in the Aleutians all lie at much higher altitudes than the highest parts of Agattu.

SOIL STRUCTURES

Turf-banked terraces[14] are well developed and widely distributed. They show prominently on aerial photographs taken from 13,000 feet. The terraces are 2–15 feet wide, 20–100 feet long, and have an outer face 2–3 feet high. The treads are covered with a mixture of loose soil and rock fragments, and the outer faces are banked with turf consisting of soil, grass, moss, and scrubby heath.

Small stone nets and stripes were seen on bare flats and gentle slopes mantled with loose soil and rock fragments. The nets are usually 12–18 inches in diameter and the stripes of corresponding width. Their fresh appearance and the lack of stabilizing vegetation suggest that they are currently active.

lems in the North American Pleistocene," *Jour. Geol.*, Vol. L [1942], pp. 570–71) has restated the disadvantages of the term "postglacial" and proposes that Pleistocene be substituted for "Quaternary." Therefore, it is suggested that the warm period following the Wisconsin simply be called the post-Wisconsin optimum.

[13] Ernst Antevs, "Postpluvial Climatic Variations in the Southwest," *Bull. Amer. Meteorological Soc.*, Vol. XIX (1938), p. 190.

[14] R. P. Sharp, "Soil Structures in the St. Elias Range, Yukon Territory," *Jour. Geomorph.*, Vol. IV (1942), p. 275.

CONCLUSIONS

At least 2,000 feet of well-bedded sedimentary rocks are exposed on Agattu. They are composed largely of amorphous silica and fine detritus derived from a volcanic terrain. The strata are gently tilted, faulted, and possibly folded. Approximately 80–90 per cent of the island consists of sedimentary rocks. Small intrusive bodies of porphyry, diabase, and trap compose the remaining 10–20 per cent.

The existence of this considerable body of sedimentary rocks in the otherwise predominantly volcanic Aleutian chain raises questions concerning the constitution and origin of the western Aleutian-Komandorskie ridge. If the Agattu beds are local, they need be of little significance; but if they are related to sedimentary rocks in the Komandorskie Islands and the Kamchatka Peninsula, a significant part of the western Aleutian-Komandorskie ridge may consist of similar materials. This would indicate an extensive basin of deposition and at least a partial diastrophic origin for the ridge.

No fossils were found in the Agattu beds; they could be Mesozoic or Tertiary. If Mesozoic, the possibility that the entire Aleutian ridge is composed in part of Mesozoic strata should be considered.

Like many other Aleutian Islands, Agattu has been almost completely covered by ice, and the marks of glaciation are fresh and widespread. Ice probably occupied at least parts of the island until the post-Wisconsin optimum. It did not survive the optimum, and there are no glaciers on the island at present. Glacial snowline was 800–1,000 feet above sea-level.

SAND GRAINS AND PERIGLACIAL CLIMATE: A DISCUSSION

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ABSTRACT

The present paper discusses the work of André Cailleux on Quaternary periglacial wind action in Europe, published during the war as a memoir of the Société géologique de France. Cailleux has outlined the periglacial zone chiefly on the basis of the distribution of wind-worn sand grains in Quaternary deposits. It is felt that this new criterion, although overextended by Cailleux, is basically sound and is additional proof for a cold, windy climate adjacent to the ice sheets—a climate demonstrated by such well-known indicators as loess and frost-produced soils.

Students of the Pleistocene are familiar with the loess belt of Europe, which extends from northern France eastward to Poland and the Ukraine. According to current European opinion, as summarized by F. E. Zeuner,[1] this belt during the glacial stages of the Pleistocene was a grass steppe characterized by cold summers and colder winters. It was separated from the ice sheet by a barren tundra zone. The cold winds induced by the ice sheet picked up the fine-grained material supplied by glaciofluvial deposition and by frost-weathering in the tundra zone and deposited it as loess on the grass steppe.

Additional evidence for strong winds adjacent to the ice sheet is the presence of wind-cut pebbles (ventifacts) in glacial deposits. Evidence for low temperatures in the periglacial zone has long been available in the abundant examples of fossil soils produced by intensive frost action. The meteorological reasons for such a cold, windy climate are outlined by C. E. P. Brooks.[2]

But what of the material intermediate in size between pebbles and loess? Does the sand show evidence of periglacial wind action, either in abrasion (like ventifacts) or in deposition (like loess)? A recent paper by André Cailleux[3] has revealed the evidence. Although deposits of wind-blown sand are not widespread in the periglacial area, Cailleux believes that the individual sand grains, whether finally deposited by water, ice, or wind, show the mark of wind abrasion during the Pleistocene.

In this study, extending over a period of ten years, Cailleux separated out a coarse sand fraction (0.4–1.0 mm.) from about three thousand samples of European Quaternary deposits. He distinguished four types of quartz sand grain: (1) angular and unworn; (2) subangular to rounded, with a shiny surface; (3) rounded with a frosted (mat, ground-glass) surface; and (4) rounded with a frosted surface but retaining traces of cement or recrystallization formed in a pre-Quaternary cycle of deposition, and thus to be eliminated in the study of Quaternary conditions of abrasion.

Types 2 and 3 are differentiated more by the surface features than by the degree of rounding. The frosted surface consists of many tiny pits and crescentic percussion marks, which disperse the light evenly and give the whole surface a

[1] "The Climate Adjoining the Ice-Sheet of the Pleistocene," *Proc. Geol. Assoc. London*, Vol. XLVIII (1937), pp. 379–95.

[2] *Climate through the Ages* (London, 1926). Pp. 439.

[3] "Les Actions éoliennes périglaciaires en Europe," *Mém. Soc. géol. France*, No. 46 (1942). Pp. 166.

rough, dull aspect, no matter which way the grain is held. The shiny surface is smooth and polished; the translucence of the grain depends upon the position in which the grain is held.

Cailleux believes that the rounded, frosted grains were produced by wind abrasion and the shiny grains by water abrasion. This theory is not new. The extended controversy concerning the relative effectiveness of wind and water in rounding sand grains has recently been summarized by W. H. Twenhofel.[4] Field observations and experiments seem to be pointing to wind as the more effective rounding-agent, bearing out the theoretical approach that wind-borne sand grains have a higher velocity, higher apparent density, more direct impacts with other grains, and, thus, greater abrasive power. The additional factors of selective transportation and of complex histories must be eliminated before generalizations are justified.

The frosted surface, most workers agree, is also best produced by abrasion in wind. It is not definitely known, however, at just what stage in the rounding the frosted surface appears. The present writer has observed subrounded and even subangular grains which have patches of frosting, usually on the more rounded portions of the grains. He has also seen well-rounded grains which are completely frosted except for places where small conchoidal chips have been broken off. Presumably, then, frosting can be formed during any stage in rounding, but in the early and middle stages it does not persist because the rate of removal of small chips is too great. In advanced stages of rounding, such chips are knocked off less frequently and frosting can be retained over the entire surface.

It is not known under what conditions the frosting can be removed. Cailleux[5] states that he was able to remove a frosted surface and develop a shiny surface on grains of calcite by aqueous abrasion representing 50 km. of travel. Rounded, shiny grains are commony associated with rounded, frosted grains.[6] Were the former produced directly from unworn grains by abrasion in water, or were they produced from frosted eolian grains during a later cycle of aqueous abrasion? Experimental work should eventually establish the answer to this problem.

Cailleux believes that the percentage of frosted grains in the coarse sand fraction studied by him is a measure of the intensity of wind action for the approximate time and place of deposition. His map of the distribution of Pleistocene frosted sand grains (Fig. 1) shows that the larger percentages (40–100) are found in a broad belt extending from northwestern Germany to Poland. As the Tertiary deposits of these areas normally contain less than 5 per cent frosted grains, the contrast is striking. This belt of frosted sand grains lies, in general, between the loess belt and the Pomeranian moraines of the last glacial stage. It is strongest in central Poland, where 80–100 per cent of the coarse sand grains are frosted. Cailleux believes that the stronger wind action thus indicated in the east is a result of greater continentality of climate. Zeuner[7] had arrived

[4] "Rounding of Sand Grains," *Jour. Sed. Pet.*, Vol. XV (1945), pp. 59–71.

[5] P. 36 of ftn. 3.

[6] H. C. Stetson, "The Sediments of the Continental Shelf off the Eastern Coast of the United States," *Papers in Physical Oceanography and Meteorology, Mass. Inst. Tech. and Woods Hole Oceonographic Inst.*, Vol. V (1938), No. 4.

[7] Ftn. 1.

at the same conclusion from the study of the loess belt, which is wider to the east. Zeuner also pointed out that the climate in the west must have been correspondingly more oceanic because of the more common occurrence in the west of (frosted) sand grains and the terminal positions of the ice sheets. However, in the case of any of the older glacial stages, there probably would not be a sufficient number of samples to justify contours with intervals as small as 20 per cent.

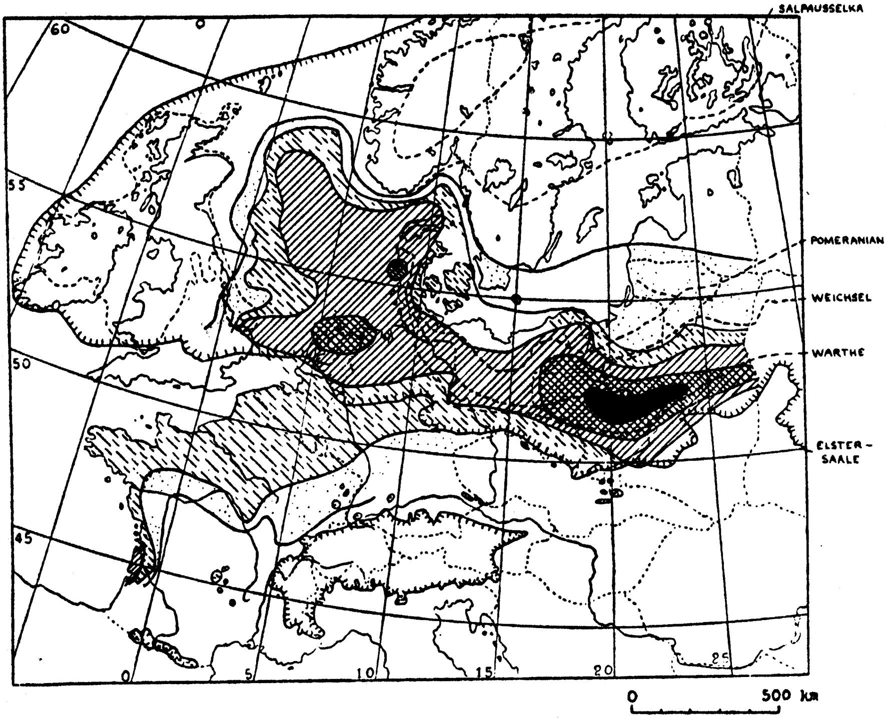

FIG. 1.—Distribution of frosted (wind-worn) sand grains in Quaternary deposits of northern and western Europe. Black pattern, more than 80 per cent of the coarse (0.4–1.0 mm.) sand grains are frosted; cross-hatched, 60–80 per cent; diagonal lines, 40–60 per cent; dashed diagonal lines, 20–40 per cent; dots, 10–20 per cent; white, less than 10 per cent. The northern margin of the loess belt coincides roughly with the barbed line which represents the Elster-Saale or maximum extension of the Quaternary ice sheets. Moraines of the last glaciation are shown by dashed lines and labels. (After Cailleux, Fig. 16 of ftn. 3.)

solifluction soils, which require a cold, moist climate.

This distribution map of frosted sand grains includes deposits of all glacial and interglacial stages of the Pleistocene. A separate map for each glacial stage would reveal more accurately the relations between concentrations of eolian Presumably, most of Cailleux's samples came from the widespread deposits of the last glacial stage, so his published composite map (Fig. 1) must show most accurately the relations for this stage. At best, the contours indicate only the general distribution of eolian grains.

The map shows that the belt of high

concentration of eolian grains lies north of the Elster and the Saale terminal moraines, in part north of the Warthe (last glaciation, phase 1) and the Brandenburg or Weichsel (last glaciation, phase 2) moraines, and entirely south of the Pomeranian or Great Baltic (last glaciation, phase 3) moraines. Therefore, most of the sand grains must have been rounded and frosted before the pre-Pomeranian ice sheets reached their terminal positions, or during the early stages of their retreats. All the ice sheets must have expanded fairly rapidly until they reached the southern coast of the Baltic Sea. The subsequent advance and retreat to and from the terminal position must have been slower and the pause at the terminal position brief. In this way a maximum amount of time would be available for wind abrasion in the areas now marked by high percentages of eolian grains.

Cailleux makes much of the low percentage of eolian grains in the deposits of the retreat from the Pomeranian moraine. He states that the decrease was caused by a rapid improvement of climate, which was not registered by an equally rapid retreat of the huge, inert ice sheet. The barren tundra zone marginal to the ice sheet was replaced by advancing forests, the winds decreased, and fewer sand grains were frosted. He even suggests that the Scandinavian ice sheet might have "waited out" the last (Riss-Würm) interglacial, which was so well represented in the smaller, more sensitive Alpine ice sheet. Such a suggestion ignores the well-established correlation of the late Scandinavian and Alpine glacial and interglacial stages. The low percentages of eolian grains in late-glacial deposits may be explained much more simply by noting that such deposits are confined to areas which were covered by ice during most of each glacial stage. The sand grains in these areas thus were not available for abrasion in the periglacial winds. Furthermore, if there was such an abrupt decrease in the number of eolian grains produced in late-glacial time, one would expect even greater decrease in interglacial deposits. The great Elster-Saale interglacial stage lasted much longer than late-glacial time and had a more temperate climate. Yet, according to Cailleux, deposits of the interglacial stages show high percentages of eolian grains (Table 1).

TABLE 1*

SECTION OF SURFICIAL DEPOSITS NEAR WARSAW

	Per Cent Coarse Sand Grains Frosted
Moraine (last glaciation)	70
Sand (last interglacial)	80
Moraine (older glaciation)	65–70
Preglacial (early Pleistocene) derived from the north	70–80
Preglacial (early Pleistocene) derived from the Carpathian Mountains	5–80
Pliocene	5

*Extracted from table on p.81 of ftn. 3.

There is little evidence for strong wind action in these areas during interglacial stages; so the frosted sand grains in interglacial deposits must have been derived from the deposits of the preceding glacial stages. It is surprising that fresh or shiny sand grains were not supplied by interglacial chemical weathering and stream abrasion in sufficient quantities to reduce the concentration of frosted grains.

Cailleux overlooks these relationships. He does not state the number of interglacial deposits sampled, the conditions of deposition, or the source of the sediment. Perhaps such details of description could not be presented because of the

large scope and reconnaissance nature of the study. In many cases the information probably was not available because the sampled deposits were inadequately studied. In other cases the samples were not collected by Cailleux himself but were sent to him by other individuals.

The accuracy of the distribution map (Fig. 1) and the correctness of the interpretations depend partly on the methods of sampling, particularly when the samples are supposed to represent all of Europe during all of the Quaternary. Half of the samples came from fluvial and lacustrine deposits; the remainder from moraines, frost-produced soils, and eolian deposits. Apparently, the sand grains were scattered over the entire barren tundra zone after having been rounded and frosted by abrasion in the wind. Final transportation and deposition by the advancing ice or by glaciofluvial streams did not change appreciably their wind-worn character or add many fresh, unworn grains. However, Cailleux does not state what percentage of the whole sample is represented by the frosted grains. A sample of boulder clay with 1 per cent coarse sand (0.4–1.0 mm.) has a different statistical value from a sample of well-sorted eolian or fluvial sand with 80 per cent coarse sand, even though 65 per cent of the coarse sand grains in each case may be rounded and frosted.

In addition to eolian sand grains, Cailleux studied the distribution of ventifacts and frost-produced soils in Quaternary deposits. He found that, in general, more ventifacts and more intense frost action have been reported from areas which have high percentages of eolian sand grains. He measured the relative intensity of frost action by noting the number of ventifacts larger than 10 cm. which were wind-worn on all sides. This novel method is based on the belief that pebbles of this size, after being worn on the face or faces exposed to the wind, were too large to be blown over by the wind and, therefore, must have been turned over by some other agent. Action of animals or undermining by wind or rainwash on sloping ground are considered to be unimportant. The fact that ventifacts are so often associated with frost-produced soils indicates that frost action was available to overturn these stones. Furthermore, this scale of intensity of frost action fits well into our general picture of the periglacial climate.

Cailleux found numerous overturned ventifacts and frost-produced soils (even ice wedges) in central and western France as far south as Bordeaux, and around the Alps. With the exception of the great ancient coastal dunes of Les Landes, there are low percentages of rounded and frosted sand grains in the Pleistocene deposits of these areas. The conditions of sand supply, sand disposal, and vegetation may have been such that no one grain could undergo enough wear to acquire a rounded and frosted character. In Iceland, for instance, ventifacts are being formed today in great abundance, but the sand grains are angular. This is the more remarkable because these grains are fragments and minerals of volcanic rock, which is less resistant to abrasion than is quartz, the dominant mineral of European periglacial areas.

In conclusion, it may be stated that Cailleux's eolian sand grains provide one more criterion useful in determining the nature of the Pleistocene periglacial climate in Europe. Some of his detailed correlations are hardly tenable, largely because his methods of sampling are either inadequate or insufficiently explained. However, his main theses may be ac-

cepted: (1) Pleistocene deposits of the periglacial area contain more eolian sand grains than Tertiary deposits of the same areas; (2) the higher percentages (40–100) of eolian sand grains are found in a belt between the loess belt and extended positions of the ice sheets; and (3) this belt is strongest to the east, where the climate was more continental. His study of the distribution of ventifacts and frost-produced soils provides confirmatory evidence. These three main conclusions fit well into our general conception of the periglacial climate as determined from other criteria, such as loess, tundra soil, and cold-type flora and fauna.

ACKNOWLEDGMENT.—The writer is greatly indebted to Kirk Bryan for criticism of this discussion.

REVIEWS

Vertebrate Paleontology. By ALFRED S. ROMER. 2d ed. $7.50. Chicago: University of Chicago Press, 1945. Pp. 687; figs. 377; tables 4.

Paleontologists and students in related fields will welcome the appearance of the second edition of Romer's *Vertebrate Paleontology* at a time which has witnessed diversion of many of their numbers to other fields of activities and sharp reduction in the interchange of information between countries. Since 1933, the date of publication of the first edition, great strides have been made in the studies of vertebrate evolution. The second edition of *Vertebrate Paleontology* takes note of the important developments and incorporates them into the story of vertebrate history. About one-half of the text has been re-written; important changes in classification have been introduced; new figures have been added; some old ones have been replaced; and important additions to the contents have been incorporated.

Certain modifications may be cited as being of particular importance. The section on the fishes has been materially increased to include a moderately extensive account of the teleosts, a group treated with disproportionate brevity in the first edition. A new classification of the amphibians has been proposed. This is an area in which Romer has been particularly active, so that his concepts take into consideration the best thought on the group and offer an intelligent co-ordination of the present status of knowledge. Two major subdivisions of the class are recognized: the subclass Apsidospondyli, which includes the superorders Labyrinthodontia and Salientia; and the subclass Lepospondyli, including not only the typical "Coal Measures" orders but the Urodela and Apoda as well. The subclass Seymouriamorpha is removed from the class Reptilia and included as an order of the superorder Labyrinthodontia. *Amphibamus* and *Miobatrachus* of the North American Pennsylvanian are recognized as ancestral Anura, following Watson, and constitute the known members of the order Eoanura.

The treatment of the reptiles has not been materially altered except for occasional modifications which take cognizance of developments of the last decade. The tritylodonts, classed as mammals in the earlier edition, are placed with the ictidosaurs, among the reptiles. The chapter on birds is little changed. The pattern of the section dealing with mammals is much the same as in the first edition except that consideration of the Primates, which constituted the last chapter in the first edition, is shifted to follow the material on primitive placental mammals. The classification, however, has been brought up to date, and the text has been altered in accord with the changes.

A notable addition to the book is three new chapters devoted to vertebrate history. In the earlier edition the reader was obliged to reconstruct this history from brief remarks in the systematic treatment, and little concerning the nature and distribution of deposits was available. This section begins with a very brief series of statements concerning correlation, the nature of evidence, effects of environmental differences on faunas, climates, and migrations. Although these furnish a basis for thought on these important matters, the treatment is so brief that many students will fail to understand the full significance of these matters. This introduction is followed by an analysis of the faunas of each period, from the Cambrian to the present. Three tables list some of the most important vertebrate-producing localities, giving their position in the appropriate continent and their approximate geological age. This section, although brief, performs an important function in making the book of greater value to the nonspecialist, particularly to paleontologically minded geologists. It also serves as an excellent summary for students who may become lost in the extensive detail of the systematic and morphologic sections.

The classification of the vertebrates, synoptic in the first edition, has been greatly expanded—from 17 pages to 54 pages. The expansion results primarily from the listing of the majority of important fossil genera and an increased number of extant types. As before, the family reference, the geological age, and the continent or continents in which genera occur are noted. The classification is comprehensive

but, of course, far from complete. The Bibliography is expanded to include recent publications as well as a more extensive series of older works. As in the first edition, comments follow many of the references. These aid the student materially in his effort to select reading materials on a particular group. The Index is enlarged, in keeping with the expansion of the classification. It is primarily taxonomic; but many morphological, geological, and geographic terms are included.

This book, as was true of its predecessor, is indispensable as a reference work in the teaching of vertebrate paleontology. It may be used as a text for a comprehensive course on phylogeny, taxonomy, general morphology, and stratigraphic and geographic distribution of the vertebrates. A student lacking background in basic vertebrate anatomy and phylogeny may, however, find himself lost in some sections of the text, as a result of the array of facts which he must master. This proved to be the case in the first edition and cannot, perhaps, be avoided in a text which follows a systematic scheme of organization and is at all comprehensive. The use of illustrative specimens with the text aids materially in reducing this difficulty. It is doubtful that a student working independently with the text without extensive collections can gain an adequate concept of the field unless he already has a strong background in related fields. The presentation of phylogeny, morphology, and general stratigraphic position and range of groups simultaneously must necessarily be difficult to follow. The segregation and amplification of stratigraphic work in the new edition goes part way in remedying this difficulty.

The format of the text has been improved by the substitution of heavy, large type for italics in the subheadings of the chapters. The illustrations are mostly by L. I. Price and in most instances are based on published figures. They are line drawings with stipple shading. It is unfortunate that a book of such importance had to be printed on the relatively inferior paper demanded by wartime restrictions. Some of the illustrations have suffered considerable loss of detail thereby.

The value of the text as a reference book has been materially increased, especially by expansion of the classification. Its value to students has been augmented by bringing recent advances into a general picture. But the increase in coverage, while certainly of value to advanced students, will make an already difficult subject even more forbidding to an elementary student. The book is of more value to the specialist in one area of vertebrate paleontology who desires some knowledge of related areas. The stratigraphic section should prove of particular value to geologists and to students of the biological sciences who wish to develop a perspective of time in evolution as an aid to their work with modern animals.

EVERETT C. OLSON

"Macquarie Island: Its Geography and Geology." By DOUGLAS MAWSON. *Australian Antarctic Expedition, 1911–1914.* ("Scientific Reports," Ser. A, Vol. V.) Sydney: Government Printer, 1943. Pp. 194; figs. 46; pls. 37; 2 maps in color. £1 15*s*.

Sir Douglas Mawson has prepared this report mainly on the basis of the survey, notes, photographs, and collections made by Leslie R. Blake during a two-year sojourn on the island. Shortly after Blake's return to Australia in 1914, he volunteered for war service; he was killed in France on almost the last day of hostilities. Mawson has added his own observations during two short visits to the island.

Macquarie lies nearly halfway between New Zealand and Antarctica, as the emerged portion of a submarine ridge that has now been traced for a length of 250 miles and apparently extends a New Zealand tectonic line. The island may be described as a mountain range, planated prior to the glacial epoch but now rising abruptly from the sea in cliffs. Faulting has been important recently and still causes frequent earthquakes.

The oldest formation recognized is Blake's Older Basic group, a thick series of basaltic flows and sills with associated tuffaceous graywacke, possibly of Tertiary age but more probably dating back to Middle Mesozoic time, and perhaps referable to the period of large-scale intrusions of dolerite into the Triassic sediments of Tasmania and Antarctica. These old rocks were intensely folded (Cretaceous? or early Tertiary?), while into the folded system were injected gabbroic magmas, which, by gravitative differentiation, have yielded a well-graded series of gabbros and peridotites. Both the grain of the folding and the long axes of the intruded masses trend northwest-southeast (pointing, it might be noted, toward Tasmania).

The axis of the present long, narrow island, however, is N. 14° E.

Erosion laid bare the plutonic masses. Later subsidence was sufficient for a deposit of globigerina ooze to be spread over the beveled structures. Magmas of the younger Basaltic group broke through this, but globigerina ooze continued to form amid the basaltic pillow lavas and breccias. Their age may be Miocene. The volcanic period ended with a land area probably larger than the present island. Pleistocene glaciation was severe.

The igneous rocks have been well studied petrographically, with accompanying tables of chemical analyses, and many of the individual specimens are described in detail. The photographic plates at the end of the report are excellent.

R. T. C.

Physiographic Diagram of Asia. By A. K. LOBECK. Small scale ed. New York: Geographical Press, Columbia University, 1945. Scale, 1:20,000,000. Separate text, pp. 8. Map sheet (24 × 38 in.). Without the text $0.35 (10 or more, $0.25 each). Map and text, $0.70 (10 or more, $0.50 each).

Professor Lobeck's well-known series of physiographic diagrams has now been extended to include Asia. This newly issued diagram, including Europe and the Dutch East Indies in opposite corners without appreciable reduction in the size of Asia, measures 22 × 24 inches. It is a clear-cut picture of Asia's facial features. On the reverse side of the sheet is a corresponding map of the physiographic provinces with the major groups, smaller units, and lesser subdivisions named and systematically numbered (or lettered) in accordance with Lobeck's classification. Owing to the large number of physiographic units recognized (no fewer than 255 smaller subdivisions), this black-and-white map is most valuable for its details. The recommended coloring, however, will doubtless make the larger relations stand out more distinctly.

Alongside the diagram is a double-column discussion in fine print of the size, location, climate, vegetation, people, history, culture, and religion of Asia. In spite of the diversity of topics handled in this limited space, the general understanding obtained by the reader is distinctly good, and the reading is by no means dull. On the map side of the sheet, a complete tabular classification of the physiographic divisions fills an entire column. An adjoining column gives instructions for tinting the diagram and coloring the map, together with much other pertinent information. The map scale of this small-size edition makes the sheet very convenient for desk use, thus obviating bothersome trips to consult wall maps and their like. Folded to about the size of a quarto page, the map sheet can be filed together with the text sheet in an ordinary desk drawer.

The text sheet is of the same size as the map sheet and is so printed on both sides that, by folding, its eight pages become arranged in proper sequence. Here is given judicially selected information on all the physiographic divisions, large and small, arranged in the order of the classification table on the map sheet. A surprising amount of useful factual material has been packed in very small space.

R. T. C.

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MARINE SOLUTION BASINS[1]

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ABSTRACT

High-tide rock basins common in calcareous rocks at La Jolla and elsewhere are described. Rock and water analyses were made in order to determine the origin of the basins. The evidence indicates that biochemical processes cause the sea water in the basins to become unsaturated with calcium carbonate at night, so that calcite cement is dissolved from the rock floor. Waves at high tide and snails living in the basins remove the uncemented rock grains. During the daytime, however, the water deposits calcium carbonate, and for the higher tide pools this deposition results in greater induration of the rock at the edge of the pools, so that resistant elevated rims are formed.

INTRODUCTION

In 1937 the author became interested in the very numerous tide pools in sandstone benches along the coast at La Jolla, California. Even casual inspection of the tide-pool basins indicates a complex origin. The shape and other characteristics show that they are in part due to solution of the rock. Solution of the calcium carbonate cement in the sandstone, however, is not a complete explanation, because the solvent, sea water, is normally saturated with $CaCO_3$. Moreover, many of the basins are surrounded by elevated rims, features suggestive of deposition rather than of solution. When opportunities presented themselves, during vacations and holidays, an investigation of the origin of the basins was made.

[1] *Contributions from the Scripps Institute of Oceanography*, N.S., No. 293.

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DISTRIBUTION AND PREVIOUS THEORIES OF ORIGIN

At La Jolla and Point Loma, California, the basins occur in sandstones of the Cretaceous Chico formation and Eocene Rose Canyon formation. The author has seen similar basins in a limestone member of the Miocene Altamira formation near San Pedro, California; in Pliocene[3] shell limestone at Cedros Island, Baja California, Mexico; in Tertiary coral limestone at Key West, Florida; in a Tertiary calcareous sandstone at San Juan, Puerto Rico; and in Pleistocene calcareous eolianite and marine limestone at Bermuda.

The basins in Bermuda were photographed and briefly described by R. W. Sayles as due to solution.[4] Basins in sand-

[3] The age was determined from enclosed fossils by Dr. B. F. Osorio Tafall (personal communication).

[4] "Bermuda during the Ice Age," *Contr. Bermuda Biol. Sta. Res.*, No. 165 (1931), Pl. 10, pp. 404, 405.

stone on the coasts of Morotai and Wotap islands, like those of Figure 3, were ascribed by P. H. Kuenen[5] to the crystallization of salt around the edges of pools of water, thus indurating that part of the rock, so that later erosion produced rimmed basins. Similar basins in limestone were described from the coastal benches of Hawaii by C. K. Wentworth,[6] who believed them due to solution by fresh water from rain or ground water. Isabel Henkel[7] suggested that basins in sandstone of Vancouver Island, Canada, somewhat like those of Figures 3 and 5, are developed by a wide variety of processes, chief of which is the weathering-out of concretions, which serve as abrasive tools to form potholes. Rimmed basins on Triassic sandstone marine benches of Australia were photographed by J. T. Jutson,[8] who offered no explanation of them. Others have been noted on Ulithi Atoll and New Guinea.[9]

Some basins found on land at considerable distance from shore possess characteristics like those of the marine basins and are believed due to solution. Such basins in limestone were described by Wentworth[10] from the interior of Hawaii. Smith and Albritton[11] found shallow basins, called *tinajitas*, in Cretaceous limestones of western Texas, which they believed resulted from solution by occasional rains and flushing of the residue by exceptionally heavy rains or by winds.

Even igneous rocks contain basins probably due to solution. F. S. Matthes[12] described basins about 45 cm. in diameter in granite and quartz monzonite of the Sierra Nevada, which he thought were formed by solution of less resistant minerals by rain water acidified by decomposing pine needles and other vegetation. Freezing water assists by loosening grains or flakes of the rock. Larger basins in granite of South Carolina are ascribed by L. L. Smith[13] to accelerated weathering by acids from the decomposition of vegetation. Water of the basins has a low pH and gives a strong test for sulphur dioxide, hydrogen sulphide, and carbon dioxide. The author also has seen similar basins up to 2 meters in diameter in granite at Elephant Rocks, Missouri. Basins described as potholes by M. B. Fuller[14] occur in schist in Colorado, but photographs show that some of the smaller ones are shallow and flat bottomed, unlike ordinary potholes; and it is possible that these particular basins are due to solution. That water containing CO_2 is competent to dissolve minerals of igneous and metamorphic rocks has been shown by several workers.[15]

5 "Einige Bilder Eigentümlicher Verwitterungsformen an tropischen Küsten (Molukken)," *Geologie der Meere und Binnengewässer*, Vol. I (1937), pp. 22–26.

6 "Potholes, Pits, and Pans: Subaerial and Marine," *Jour. Geol.*, Vol. LII (1944), pp. 117–30.

7 "A Study of Tide-Pools on the West Coast of Vancouver Island," *Postelsia: The Yearbook of the Minnesota Seaside Station* (1906), pp. 277–304.

8 "Shore Platforms near Sydney, New South Wales," *Jour. Geomorph.*, Vol. II (1939), pp. 237–50.

9 W. H. Easton, James Gilluly, W. C. Putnam, personal communications.

10 *Idem.*

11 J. F. Smith, Jr., and C. C. Albritton, Jr., "Solution Effects on Limestone as a Function of Slope," *Bull. Geol. Soc. Amer.*, Vol. LII (1941), pp. 61–78.

12 "Geologic History of the Yosemite Valley," *U.S. Geol. Surv. Prof. Paper 160* (1930), p. 64, Pl. 33.

13 "Weather Pits in Granite of the Southern Piedmont," *Jour. Geomorph.*, Vol. IV (1941), pp. 117–27.

14 "The Bearing of Some Remarkable Potholes on the Early Pleistocene Glaciation of the Front Range, Colorado," *Jour. Geol.*, Vol. XXXIII (1925), pp. 224, 225.

15 Richard Müller, "Untersuchungen über die Einwirkung des Kohlensäurehaltigen Wassers auf einige Mineralien und Gesteine," *Tschermak Min. Mittheil.*, Vol. VII (1877), pp. 25–48.

DESCRIPTION OF BASINS

RELATION TO TIDE

Near La Jolla, tide-pool basins are very well developed along 2 km. of the coast where a bench of Cretaceous sandstone slopes gently toward the sea. The basins are within the area exposed at mid-tide beyond the foot of a low sea cliff which is reached by only the very highest tides. A cross-sectional strip near Whale View Point, extending the 30 meters distance from the cliff across and beyond the bench to the mid-tide line and having a width of 6 meters, was selected for a quantitative study of the basins. The 30-meter length of the strip was divided into ten zones, each 3 meters by 6 meters in dimensions. All basins of each zone were counted and measured, with results as shown in Figure 1.

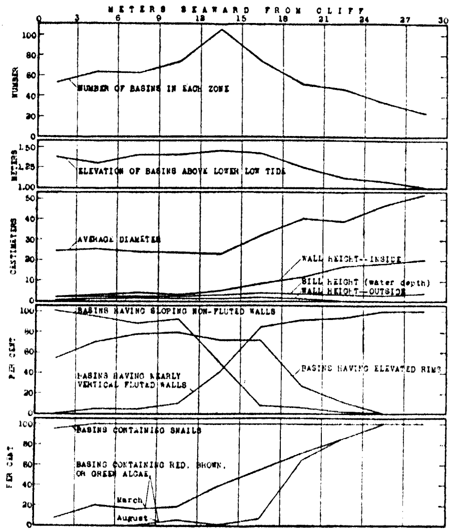

FIG. 1.—Variation of elevation, number, diameter, depth, and other characteristics of solution basins found in ten zones extending from a sea cliff to the mid-tide line 30 meters seaward.

The elevation of the basins ranges from 1.45 meters above mean lower low tide near the outer part of the bench to 1.00 meter in the zone farthest seaward beyond the bench. For comparison, at La Jolla, the mean tide range is 1.10 meters, with mean high tide about +1.45 meters and mean low tide about +0.35 meter above mean lower low tide. However, extreme tides of +2.30 meters and −0.55 meter occur during the year.[16] The tide

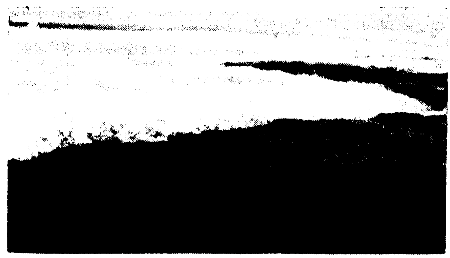

FIG. 2.—Renewal of sea water in basins at high tide.

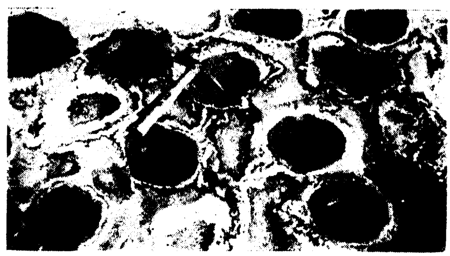

FIG. 3.—Basins characteristic of 9–12-meter zone, showing sea salt deposited from evaporation of water after a warm day of low tides (May, 1944).

range is sufficient to cause a daily and sometimes a semidaily refilling of all the basins (Fig. 2) except during calm neap-tide periods, when the highest basins may not be refilled for several days, so that their content of water may entirely evaporate, as in Figure 3.

SIZE AND SHAPE

As shown by Figure 1, the basins are most numerous on the higher parts of

[16] "Tide Tables, Pacific Ocean and Indian Ocean for the Year 1944," *U.S. Coast and Geod. Surv.*, Serial No. 653, pp. 66–69, 275.

the bench in the 9–18-meter zones, which contain mostly the type illustrated in Figure 4. Shoreward the basins are fewer in number, presumably because of being in an earlier stage of development. Seaward they are less abundant because of their larger diameter, resulting partly from the coalescence of adjacent basins (Fig. 5). Figure 1 shows that, as the diameter increases, the depth of the basin below the top of its surrounding wall also becomes greater, so that the basins farthest seaward are both broadest and deepest. However, it should be noted that, in spite of the greater inside wall height of the seaward basins, the depth of water which they can retain is not much greater than that for the shallower basins landward. This apparently is due to downcutting of their outlets, as illustrated in Figure 6.

FIG. 4.—Basins characteristic of 15–18-meter zone. Note presence of elevated rims and relatively flat bottoms. Rims are covered by evaporating water drawn by capillarity from the basins (January, 1944).

FIG. 5.—Basin of 18–21-meter zone representing the coalescence of at least four basins. Note the elevated rims having vertical fluted inner walls and the presence of snails within some of the flutings (January, 1944).

Most of the landward basins are nearly circular in outline; but many of those farther seaward are very irregular, having shapes indicative of the coalescence of several smaller basins.

An outstanding feature of the top of the bench is the presence of volcano-like elevated rims surrounding the basins, as shown in Figures 3, 4, and 5. The top of the rim is usually 2–8 cm. higher than the bottom of the basin, but it may also reach 1–5 cm. above the level of the rock surface outside the basin. In the area studied, the bottom of each rimmed basin lies at a lower level than the surrounding rock surface. The rim is less pronounced in the seaward basins and is rarely present beyond the 15–18-meter zone (Figs. 1 and 6). Another interesting characteristic of the walls of basins on the outer part of the bench and farther seaward is the presence of flutings or shallow vertical concavities extending from the top to the bottom of the inner face of the walls (Figs. 5 and 6). Walls having these flutings are usually nearly vertical. The walls of shoreward basins

FIG. 6.—Basins characteristic of the 21–24-meter zone. Note the high vertical fluted walls and the shallow depth of water resulting from the downcutting of the outlets. The elevated rims of basins in zones farther landward are absent (January, 1944).

rarely show this fluting but, instead, are smoothly rounded and slope gently toward the bottom of each basin (Fig. 3). As shown in Figure 1, practically all the basins in zones from 0 to 12 meters have gently sloping nonfluted walls, while nearly all those from 15 to 30 meters have steep fluted walls.

In other areas near La Jolla, basins have sizes and shapes similar to those discussed; however, basins of some of these areas have no elevated rims (Fig. 7), and in other areas the rims rise as much as 25 cm. above the surrounding

FIG. 7.—Basins having very deep flutings, many of which contain snails. Elevated rims are not present (November, 1943).

rock surface. Most of the examples of very high rims are exceptional and appear to be remnants of the pedestals originally supporting concretions which were weathered out and finally fell away. Elsewhere at La Jolla there are areas of more irregular basins, like those of Figure 8. Basins found at Cedros Island, Bermuda, and Puerto Rico also resembled those of Figure 8, while those at San Pedro were modified by the presence of numerous closely spaced calcite-filled cracks.

Examination of Figure 1 shows that the basins are large in diameter, compared to their depth; and the photographs show that the bottom of most basins is flat. In a few basins, however, rocks have been introduced at some time and have been retained long enough for the basin to develop into a pothole (Fig. 9). These potholes are deep and narrow and have smooth, unfluted, and relatively hard-surfaced walls. Similar transformation of solution basins into

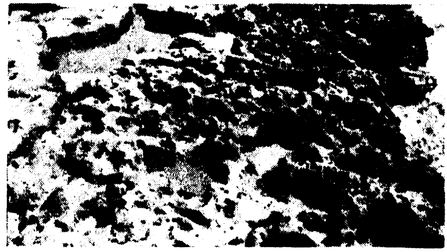

FIG. 8.—Irregular basins in sandstone near the Scripps Institution of Oceanography (August, 1945).

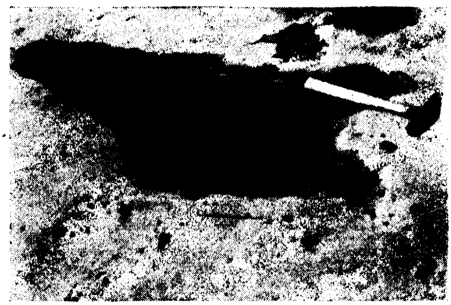

FIG. 9.—Pothole formed in solution basin. Note the smooth deep walls of the pothole and the fluted walls and remnants of the shallow bottom of the original solution basin (July, 1945).

potholes has been noted by E. D. Elston[17] and by Wentworth.[18]

LITHOLOGY

The basins which were most completely studied occur in Cretaceous Chico sandstone. Along the shore the sandstone consists of very gently dipping beds, usually less than 3 meters thick and sepa-

[17] "Potholes: Their Variety, Origin and Significance," *Sci. Monthly*, Vol. V (1916), pp. 554–67; Vol. VII (1918), pp. 37–51.

[18] *Op. cit.*

rated by shale partings. Some contain ripple marks, minor depositional folds, and numerous concretions. Where unweathered, the rock is medium gray and is firmly cemented. Weathered surfaces are dark gray and friable, but too strong to be crushed in the hand. No stains characteristic of weathered pyrite are present. The Eocene Rose Canyon sandstones in which some basins are found have similar lithologic characteristics.

Samples of rock were collected from five basins and investigated for their content of $CaCO_3$. Microscopic examination showed that calcite is present only as cement between detrital sand grains. Percentage of $CaCO_3$ was determined after the samples were crushed and treated with 1 normal hydrochloric acid. Typical results are shown in Figure 10, a scale drawing of the position of rock samples collected from two basins, superimposed on a photograph of one similar typical basin. In general, the highest percentage of $CaCO_3$, 8.8–10.1, was found in samples consisting of scrapings from the walls. The samples scraped from the inner wall were found to have a slightly higher content than those from the outer wall of elevated rims. Samples taken at progressively greater depths within the rims have less cement, 7.9–

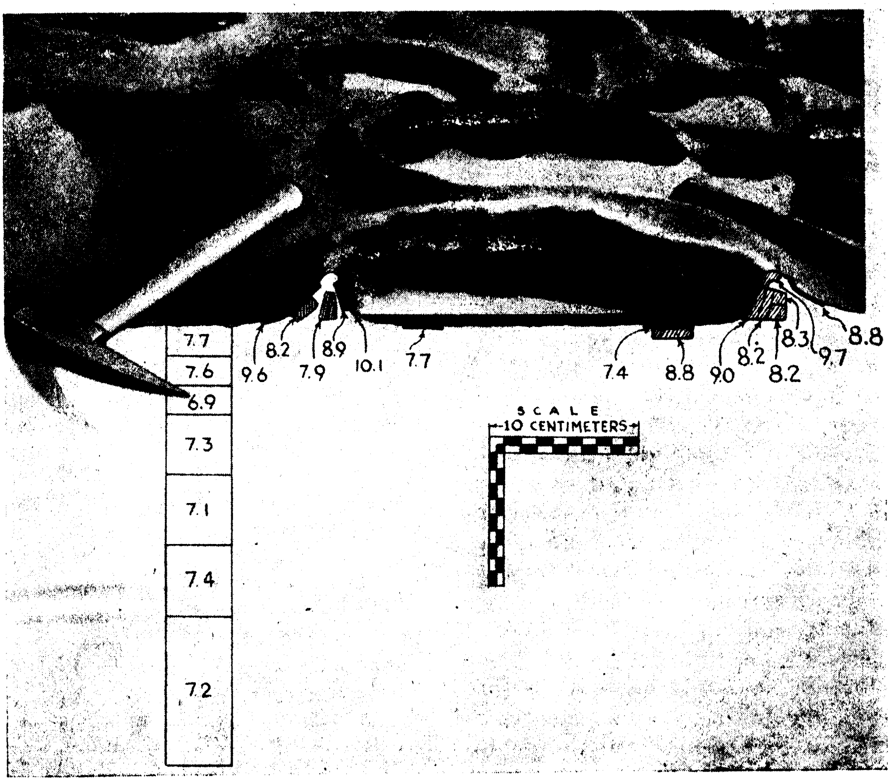

FIG. 10.—Composite photograph and drawing showing the percentage of calcium carbonate in rock samples collected from various parts of two different basins. (Drawn by Mr. Sam Hinton.)

8.3 per cent. For both basins the lowest percentage of $CaCO_3$, 7.4 and 7.7, was found in samples composed of scrapings from the bottom, which is ordinarily covered by water. A hole, drilled to a depth of 30 cm. outside one of the basins and 20 cm. from the rim, yielded samples

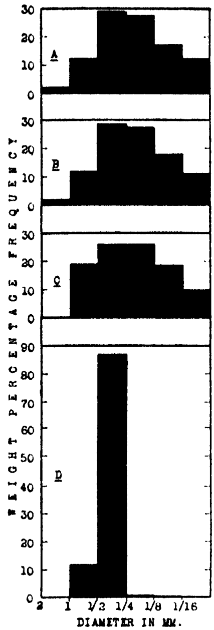

FIG. 11.—Histograms showing size distribution of sand grains from insoluble residues of (*A*) sandstone, 20 cm. from basin rim, 2–4 cm. deep; (*B*) sandstone, from basin rim, 1 cm. deep; (*C*) sand from *L. planaxis* collected from basin of Fig. 5; and (*D*) sand from beach, 20 meters distant from samples *A*, *B*, and *C*.

which varied irregularly from 7.7 per cent $CaCO_3$ near the surface to 7.2 per cent at the bottom. For comparison, beach sand 25 meters distant from the sandstone samples was found to contain only 1.6 per cent $CaCO_3$, probably all in the form of shell fragments.

The insoluble residue was of the rock sample collected from a depth of 2–4 cm. in the drill hole and of another sample from the center of a basin rim was sieved, revealing almost identical grain-size distributions, as shown in Figure 11. The median diameter of grains in both sandstone samples is 0.210, classifying them as fine sands. Both samples are poorly sorted and contain even some very coarse sand grains. Microscopic examination of the sand grains showed them to be angular in shape and composed of the minerals listed in Table 1. This analysis was made by Dr. Thomas Clements.

TABLE 1

MINERAL COMPOSITION OF INSOLUBLE RESIDUE OF SANDSTONE

	Percentage
Light minerals:	
Quartz	40
Orthoclase	45
Plagioclase (oligoclase-andesine)	10
Heavy minerals	5
Biotite—very abundant	
Chlorite—a few grains	
Hornblende—a few green grains	
Magnetite—rare grains	
Serpentine?—rare grains	

ORGANISMS OF THE BASINS

A wide and varied community of plants and animals live together in the basins. Some of them live only in the higher basins, while others occur only in low basins, where occasional splashes of water or spray prevent complete drying out during low tide. The longer exposure of the higher basins also results in a higher maximum temperature during the day, a limiting factor for marine life.[19]

There are marked changes in the number and species of algae in the basins throughout the year, with greatest abundance during winter, when the tide-pool water is coldest and the sunlight is not too strong. As illustrated in Fig-

[19] A. B. Klugh, "Factors Controlling the Biota of Tide-Pools," *Ecology*, Vol. V (1924), pp. 192–96.

ure 1, during March less than 20 per cent of the basins in the 0–12-meter zones contain attached red, brown, or green algae, in contrast to the 24–30-meter zones farther seaward, where all basins contain some algae. Counts made during August show that fewer basins in all zones contain algae. The basin illustrated in Figure 5, for example, was barren of algae in August. A collection of algae, believed to be fairly representative, was made in March and in August. The specimens were identified by Dr. E. Yale Dawson, whose list is given in Table 2, together with information on microscopic algae examined by Professor W. E. Allen. That the collection was not exhaustive is suggested by the large number of algae known to occur in the intertidal zone elsewhere near La Jolla.[20]

TABLE 2

ALGAE IN THE BASINS

RED ALGAE:	
Endocladia muricata	Very abundant in outer basins
Polysiphonia simplex	Abundant in August
Centroceras clavulatum	Occasional
Corallina gracilis f. densa	Occasional
Gelidium crinale	Occasional
Gigartina canaliculata	Occasional
Laurencia pacifica	Occasional
Lithophyllum decipiens	Occasional
Petrocelis sp.	Occasional
Rhodoglossum affine	Occasional
BROWN ALGAE:	
Ralfsia sp.	Abundant
Ectocarpus granulosus	Abundant in March
Colpomenia sinuosa	Occasional
Petrospongium gelatinosa	Occasional
GREEN ALGAE:	
Chaetomorpha californica	Abundant
Cladophora sp.	Occasional
Enteromorpha sp. (juvenile)	Occasional
Ulva californica	Occasional
BLUE-GREEN ALGAE	Abundant
DIATOMS (sedentary species)	Occasional
DINOFLAGELLATES	Occasional

Animals collected from the basins at the same time are listed in Table 3. Most of them are commonest in the 21–30-meter zones, and some occur only in those zones. A prominent exception, however, are the *Littorinas*, which were found in nearly every basin of all zones.

During the investigation it was discovered that a large number of sand grains were excreted by *Littorinas*. Examination of the intestines of these snails by Dr. W. R. Coe showed them to be jammed with sand grains and sessile blue-green algae. In order to obtain a large sample of the ingested sand, 2,600 individuals of *Littorina planaxis* were collected from the basin shown in Figure 5. These had a total weight of 87.5 gm. and probably amounted to three-fourths of all the snails living in that basin, the remainder being very small individuals. During the first 24 hours, the 2,600 snails excreted 0.311 gm. of sand, or 0.00012 gm. per snail. No additional sand was excreted during the following 24 hours. A separate collection of 104 very large specimens yielded an average of 0.0015 gm. each. After disaggregation and removal of organic matter with hydrogen peroxide, followed by 1 normal hydrochloric acid, the catch from the first group was sieved. The size distribution of the grains is shown in Figure 11. It should be noted that the shape of the histogram is very similar to those of the insoluble residues of the sandstone in which the basins are formed. The only other likely source of sand for the snails was a small beach about 25 meters distant, but Figure 11 shows that the size

[20] E. Yale Dawson, "An Annotated List of the Marine Algae and Marine Grasses of San Diego County, California," *San Diego Soc. Nat. Hist., Occas. Paper No. 7* (1945).

distribution of the beach sand is entirely different from that excreted by the snails. The median diameter of the snail sand was 0.220 mm., very close to the value of 0.210 mm. for the sandstone, in comparison with the 0.350-mm. median diameter of the beach sand. It therefore seems likely that the sand ingested by the snails was obtained from the surface of the rock in or near the basins by means of their filelike radulas, with which they scrape detritus and microscopic plants from the rock surface.[21] In this process of collecting food, numerous grains of the rock are included. It is evident, therefore, that the snails are agents active in the erosion of the sandstone marine benches. If the weight of sand ingested by snails is about constant throughout the year, extrapolation suggests that snails living on a sandstone bench 30 meters wide and 100 meters long are capable of eroding about 500 kg. of the sandstone per year. After excretion the coarser grains are probably added to the beaches by the waves, and the finer grains are carried seaward.

TABLE 3

ANIMALS IN THE BASINS

MOLLUSCA:	
Littorina planaxis	Very abundant
L. scutalata	Common
Tegula funebralis	Common
Acmaea persona	Common
A. cassis pelta	Occasional
Callistochiton crassicostatus	Occasional
Lepidochitona hartwegii	Occasional
Mytilus californianus	Occasional in outer basins
ARTHROPODA:	
Copopoda	Abundant
Balanus glandula	Common
B. tintinnabulum californicus	Occasional in outer basins
Pachyrapsus crassipes	Occasional in outer basins
Amphipoda	Occasional
Isopoda	Occasional
ANNULATA:	
Polychaeta worms	Occasional
COELENTERATA:	
Cribrina xanthogrammica	Occasional in outer basins

[21] E. F. Ricketts and Jack Calvin, *Between Pacific Tides* (Stanford, Calif.: Stanford University Press, 1939), pp. 14, 21, 22, Pl. I.

WATER OF BASINS

ANALYSES

Early in the investigation it was believed that the composition of the water found in the basins would be a clue to their origin. Accordingly, water samples were collected at intervals during one day in November and another day in December, 1943, from twenty-one basins of all types. The water temperature varied from about 7.°5 C. in the early morning to about 24.°0 C. in the afternoon. Similarly, the average pH at 0530 hours (5:30 A.M.) was 8.12 and at 1900 hours (7:00 P.M.), 8.62. Intermediate values were found at 0900 and 1500 hours (9:00 A.M. and 3:00 P.M.). Samples collected from the ocean during this period had a pH of 8.00–8.20. For comparison, a few measurements made in August, 1945, showed afternoon temperatures of 34.°5 C.

A more complete study was made during April and May, 1944, of eight basins representative of most of the zones of Figure 1. Water samples were collected in two series, the first of which was a 28-hour period of April 27 and 28, which was interrupted at night by the renewal of water at high tide. In order to obtain data on water characteristics during a night, another series, of 12 hours length, was collected a week later, May 5 and 6,

when the tidal cycle had progressed so that night was the time of low tide instead of high tide. At 2- or 3-hour intervals in each series, water samples were obtained in two 100-ml. citrate bottles, held just at the surface so that water flowed in without bubbling. The bottles were tightly stoppered and carried in a dark cool container to the laboratory, where a pH measurement was made immediately. All samples were then stored in the dark at 5° C. while the other analyses were made. All analyses were completed within 4 days after collecting.

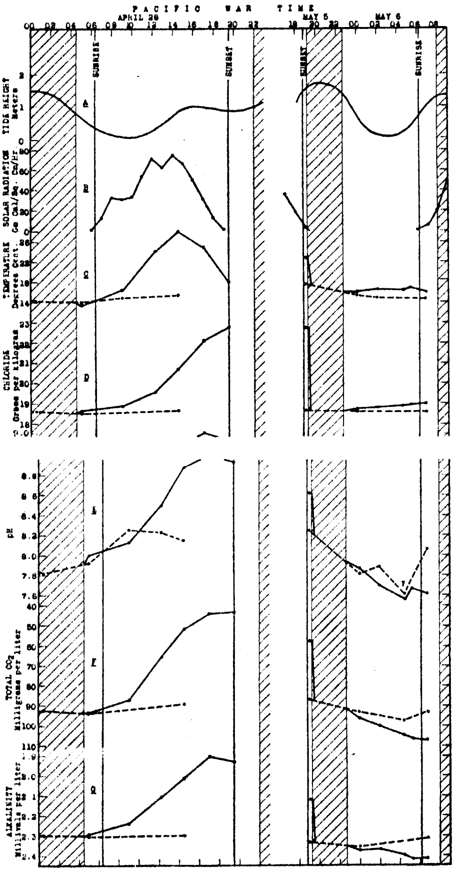

FIG. 12.—Diurnal variation of water characteristics of the basin shown in Fig. 5. Dashed line shows variation for ocean water collected near the basin. Crosshatching indicates flooding of basin at high tide.

On the basis of the pH measurements, all samples collected from one basin were selected for more complete study, together with those from the ocean and a few from the other basins. The basin chosen (Fig. 5) has a surface area of about 0.50 square meter and a water volume of 17 liters. The results of these analyses are given in Figure 12, which also includes the tide curve (*A*) and routine measurements of solar radiation by a pyrheliometer at Scripps Institution (*B*). During the day the sun's radiation was sufficient to raise the temperature of the basin water from 13°.3 C. (*C*) in the morning to 28°.0 C. in the afternoon. The afternoon temperature of the basin water was high, in contrast to the relatively constant temperature of the nearby ocean surface: 13°.8–17°.5 C. During the night the temperature of the water in all basins investigated was from 1° to 3° higher than that of the sea and of the air. Computations show that this apparently resulted from the fact that during the day only about 80 per cent of the heat from incident radiation was used in evaporation, back radiation, and temperature increase of the water.[22] The remainder of the heat was probably transferred to the rock beneath the basin, the rock serving as a heat reservoir, which returned this heat to the water during the night.

The rise of temperature during the day resulted in evaporation of some of the sea water in the basin, so that the chloride ion, determined by titration with silver nitrate,[23] increased from 18.50 to

[22] H. U. Sverdrup, M. W. Johnson, and R. H. Fleming, *The Oceans* (New York: Prentice-Hall, 1942), pp. 62, 111.

[23] *Ibid.*, p. 50.

22.79 parts per thousand (Fig. 12, *D*). These values correspond respectively to salinities, or total salt contents, of 33.42 and 41.17 parts per thousand, and to specific gravities of 1.0251 and 1.0301 if there were no deposition of salt.[24] The chlorinity change indicates that about 19 per cent of the water in the basin evaporated. A smaller increase of chlorinity was found during the night series.

The pH (Fig. 12, *E*), measured by a Beckman-type meter having a glass electrode, was found to exhibit a diurnal cycle similar to that shown by the limited measurements made during winter. During the day it rose from about 7.90 at sunrise to 9.00 at 1630 hours, after which it dropped again near sunset. In the night series, the pH dropped from 7.93 at sunset to 7.56 at 0430 hours, but near sunrise it rose again before the basin water was renewed at high tide. Water collected from the ocean near by showed a similar but more moderate variation, ranging between a pH of 7.61 (?) at night to 8.26 during the day. Such a large variation of pH in sea water is probably restricted to the shallow area near the rocky shore, because numerous samples collected by E. G. Moberg[25] off a sandy beach and from the open ocean 5 and 10 miles west of La Jolla had a pH usually between 8.1 and 8.2, respectively.

Total CO_2 was determined, using a modification of the Van Slyke manometric gas apparatus.[26] It was found to vary inversely with pH; but, for ease of comparison, it is shown in Figure 12, *F*, with an inverted scale. During the day, total CO_2 decreased from about 90.00 mg. per liter at sunrise to 43.31 mg. per liter just before sunset. During the night it increased from about 92.00 mg. per liter at sunset to 107.28 mg. per liter at sunrise.

A variation parallel to that of total CO_2 was found for alkalinity, or milliequivalents of carbonic and boric acid components combined with calcium.[27] This is also known as "titratable base" and "excess base." As shown in Figure 12, *G*, alkalinity decreased from about 2.300 milliequivalents per liter at sunrise to 1.905 milliequivalents per liter at 1700 hours. At night it increased from about 2.355 milliequivalents per liter at sunset to 2.420 milliequivalents per liter just before sunrise.

In addition to the analyses shown in Figure 12, a few of the samples were tested for free ammonia, using Nestler's reagent. All tests were negative, indicating that ammonia, if present, exists in amounts less than 0.4 mg. per liter.

RELATION TO ORGANISMS

As a result of their life-processes, animals use O_2 and form CO_2. In aquaria the CO_2 given off by fish and invertebrates gradually accumulates, forming carbonic acid and causing a lowered pH.[28] Plants in their respiration also convert O_2 to CO_2, but this is overbalanced during the daytime by the reverse process of photosynthesis, in which CO_2 and H_2O are converted into carbohydrates, which are stored, and O_2, which is set

[24] Martin Knudsen, *Hydrographical Tables* (Copenhagen: G. E. C. Gad, 1901), pp. 18, 22, 41, 42.

[25] "The Hydrogen Ion Concentration of Seawater off the Coast of Southern California," *Proc. 3d Pan-Pacific Sci. Cong., Tokyo* (1926), pp. 221–29.

[26] D. M. Greenberg, E. G. Moberg, and E. C. Allen, "Determination of Carbon Dioxide and Titratable Base in Sea Water," *Indust. Eng. Chem., Anal. Ed.*, Vol. IV (1932), pp. 309–13.

[27] *Ibid.*

[28] E. M. Brown, "Notes on the Hydrogen Ion Concentration, Excess Base, and Carbon-Dioxide Pressure of Marine Aquarium Waters," *Proc. Zoöl. Soc.*, Part 4 (1929), pp. 601–13.

free.[29] During the night, therefore, plants can be expected to increase the CO_2 content of the water in the tide pools by respiration, as do the animals; but in the daytime, to reduce it by photosynthesis. This is reflected in a low pH during the night and a high pH during the day. F. W. Gail,[30] for example, found that the pH of tide pools in Puget Sound varied between 7.43 just before sunrise and 8.80 in the afternoon. E. B. Powers[31] found nearly as great variation in a small lagoon in Puget Sound. Larger bodies of water, such as bays, show the same type of variation in pH; but, because of the large volume of water, compared to volume of organisms, the fluctuation is less extreme. E. G. Moberg[32] found that the pH of water in Mission Bay, near San Diego, changed from 7.87 at night to 8.13 during the day. Similarly, J. R. Bruce[33] found the pH of water in Port Erin Bay highest at near-shore stations and during the summer months, when photosynthetic activity was greatest; but he reported only results obtained from measurements made during the daytime. The greatest extremes in pH of water from bays seem to be encountered during ebb tides, when the water is drained from extensive areas covered by plants and animals.

As a check of the ability of the predominant tide-pool animal, *L. planaxis*, to produce a lowered pH, about twenty of the snails were placed in each of two dishes, each containing about 200 cc. of unfiltered sea water and a few chips of rock from a tide-pool wall. The rock chips had a thin coating of microscopic algae. Two other dishes contained only the sea water. One dish with snails and rock chips and one with sea water alone were placed in a dark constant-temperature room set at 15° C., while the other pair was put in sunlight during the day and removed to the dark room at night. Measurements of pH in all dishes were made with the aid of Mr. Gregory Jankowsky at 0900 and 1600 hours on several successive days. As shown in Table 4, the pH of dishes kept always in the dark showed a nearly regular decrease from the original value of 8.38. At the end of the period the pH of the dish containing water, snails, and rock chips had decreased to 7.68, while that for the dish containing only water was 8.00, the difference probably being due to the greater amount of CO_2 given off by the snails compared to that given off by microscopic plants in the dish which contained no snails. Of the other pair of dishes, the one containing only water also showed a regular decrease of pH, presumably again because the microscopic life present was insufficient to give off much CO_2 at night or to use much during the day. The other dish, however, showed an interesting variation of pH between about 8.2 in the afternoon and 7.7 at night, clearly indicating that during the night the snails gave off a considerable amount of CO_2 but that during the daytime the plants

[29] M. C. Sargent and J. C. Hindman, "The Ratio of Carbon Dioxide Consumption to Oxygen Evolution in Sea Water in the Light," *Jour. Marine Res.*, Vol. V (1943), pp. 131–35; S. M. Marshall and A. P. Orr, "The Photosynthesis of Diatom Cultures in the Sea," *Jour. Marine Biol. Assoc.*, Vol. XV (1928), pp. 321–60.

[30] "Hydrogen Ion Concentration and Other Factors Affecting the Distribution of Fucus," *Puget Sound Marine Sta. Pub.*, Vol. II (1920), pp. 287–305.

[31] "The Variation of the Condition of Sea-Water, Especially the Hydrogen Ion Concentration, and Its Relation to Marine Organisms," *Puget Sound Marine Sta. Pub.*, Vol. II (1920), pp. 369–85.

[32] "Effect of Tidal Changes on Physical and Chemical Conditions of Sea Water in the San Diego Region," *Bull. Scripps Inst. Oceanog.*, Vol. I (1927), pp. 1–14. Note that the published values were later found to be 0.27 too high.

[33] "Seasonal and Tidal pH Variations in the Water of Port Erin Bay," *38th Ann. Rept. Oceanog. Dept. Univ. Liverpool* (1924), pp. 35–39.

were able to utilize all the CO_2 given off. The afternoon pH of this dish was higher than the one containing only sea water because there was somewhat more abundant plant life on the rock chips than in the water.

A diurnal cycle of pH was also found in all the tide pools examined. This is well illustrated by Figure 12, *E*, which shows that pH rose to 9.00 in the afternoon and decreased to 7.56 just before sunrise, in contrast to the normal variation in the open sea of between 8.0 and 8.2. This resulted from the diurnal variation of CO_2 in the tide pools (Fig. 12, *F*) between 43.3 mg. per liter in the afternoon and 107.3 mg. per liter just before sunrise. By using the equations and tables summarized by Sverdrup, Johnson, and Fleming,[34] at the existing temperature, chlorinity, and $[H_2CO_3]$, the partial pressure of CO_2 in the basin at night was found to be 1.60 Torr, in contrast to the usual partial pressure of CO_2 in air of about 0.23 Torr. Thus, at night the plants and animals may have liberated more CO_2 in respiration than the water analyses indicate, the remainder having escaped into the air. On the other hand, during the day the partial pressure of CO_2 in the basin water was only 0.012 Torr, well below the partial pressure in air, 0.23 Torr. Accordingly, during the day additional CO_2 may have dissolved in the water from the air, so that the algae may have used more CO_2 in photosynthesis than the analyses indicate. The fact that the water surface was not stirred or rippled by the wind suggests that the difference may not be great, however.

TABLE 4

LABORATORY TEST OF THE EFFECT OF ORGANISMS ON pH OF SEA WATER

Dish	Treatment	pH						
		Nov. 30	Dec. 1		Dec. 2		Dec. 3	
		1600	0900	1600	0900	1600	0900	1600
Water, snails, and rock chips	Dark, night and day	8.38	7.90	7.70	7.75	7.70	7.70	7.68
Water only	Dark, night and day	8.38	8.25	8.05	8.10	8.00	8.00	8.00
Water, snails, and rock chips	Dark at night, sun in day	8.38	7.90	8.15	7.70	8.18	7.70	8.10
Water only	Dark at night, sun in day	8.38	8.28	8.10	8.10	8.00	8.03	8.03

SOLUBILITY OF CALCIUM CARBONATE

The most direct method of determining whether $CaCO_3$ is precipitated or dissolved by the water in the basins would be to measure the change of calcium ion in water samples collected at intervals during the day and night. The total salts of sea water constitute about 3.5 gm. per liter, and only about 1.2 per cent of this is calcium. Moreover, only about 11 per cent of the calcium is combined as carbonate and bicarbonate. Changes in calcium content related to changes in carbonate and bicarbonate of the water must, therefore, be minute and probably smaller than the error of the gravimetric analysis of calcium.

Another method of attacking the problem is through investigation of the variation of the anions with which calcium could be combined. About 89 per cent of

[34] *Op. cit.*, pp. 191, 201, 202.

the calcium can be assigned to chloride and sulphate; and most of the rest is combined with carbonate, bicarbonate, or borate ions. Since $CaSO_4$ and $CaCl_2$ are much more soluble and are less affected by temperature and other factors, they will remain in solution until after much of the $CaCO_3$ is precipitated. Moreover, for lack of a source of more chloride and sulphate ions, new calcium is not likely to be dissolved from the rock and combined as $CaSO_4$ or $CaCl_2$. Biochemical activities, however, do constitute a source of extra CO_2, which may be added as H_2CO_3 to the $CaCO_3$ of the rock to form the more soluble $Ca(HCO_3)_2$. The biochemical processes may also deplete the CO_2 content of the water, tending toward the reverse condition of deposition of $CaCO_3$ under certain conditions. The fact that there exists a means by which the solubility of $CaCO_3$ can vary, that the water is nearly saturated with $CaCO_3$, and that $CaCO_3$ is the first form in which calcium may be deposited during evaporation indicates that study of the variation of carbonic acid components may aid in solving the problem of the origin of the tide pools. The problem of the solubility of $CaCO_3$ in ocean water has been of interest for many years because of its dependence on biological activities and because of relationships with abundant marine sediments high in $CaCO_3$, contributed partly as shell and skeletal debris but also as true precipitates; therefore, the basic constants and equations have been determined fairly accurately.

The first step is the calculation of the amount of carbonate, bicarbonate, carbonic acid, and borate ions present in each water sample collected from the basin. The basic data for the computations are given in Figure 12. The necessary equations are derived and explained by Sverdrup, Johnson, and Fleming[35] in a concise summary of the scattered reports of studies made by K. Buch, R. H. Fleming, H. W. Harvey, E. G. Moberg, Roger Revelle, H. Wattenberg, and others. A slight modification of the four basic equations was used,[36] as follows:

$$[HCO_3^-] = \frac{[\Sigma CO_2]}{\frac{[H^+]}{K_1'} + \frac{K_2'}{[H^+]} + 1},$$

$$[CO_3^=] = \frac{[\Sigma CO_2]}{\frac{[H^+]}{K_1'} + \frac{K_2'}{[H^+]} + 1} \times \frac{K_2'}{[H^+]}$$

$$[H_2CO_3] = \frac{[\Sigma CO_3]}{\frac{[H^+]}{K_1'} + \frac{K_2'}{[H^+]} + 1} \times \frac{[H^+]}{K_1'},$$

$$[H_2BO_3^-] = \frac{K_B' \times [\Sigma H_3BO_3]}{[H^+] + K_B'} - [H^+] + \frac{K_W}{[H^+]}.$$

The first and second dissociation constants for carbonic acid needed to solve

[35] *Op. cit.*, pp. 195–202.

[36] Abbreviations and symbols are:

$[\ ]$ = gram-atoms per liter
$[A]$ = total alkalinity = $[HCO_3^-] + 2[CO_3^=] + [H_2BO_3^-]$
$[A_{CO_2}]$ = alkalinity due to carbonic acid components = $[HCO_3^-] + 2[CO_3^=]$
$[H^+]$ = hydrogen-ion concentration = 10^{-pH}
K_1' = first dissociation constant for carbonic acid = $10^{-pK_1'}$
K_2' = second dissociation constant for carbonic acid = $10^{-pK_2'}$
K_W = ion-product constant for water = 10^{-pK_W}
K_B' = apparent first dissociation constant for boric acid = $10^{-pK_B'}$
Cl = chlorinity = chlorine in grams per kilogram of water, o/oo
Chlorosity = chlorinity expressed as grams per 20° C. liter of water
T = temperature in degrees centigrade

these equations can be computed from the following:

$$pK_1' = 6.47 - 0.188\sqrt[3]{\mathrm{Cl}} + 0.006\,(20.0 - T)\,,$$

$$pK_2' = 10.288 - 0.443\sqrt[3]{\mathrm{Cl}} - 0.0046\,\mathrm{Cl} + 0.011\,(20.0 - T)\,.$$

The apparent first dissociation constant of boric acid and the ion-product constant for water can be expressed as

$$pK_B' = 9.22 - 0.123\sqrt[3]{\mathrm{Cl}} - 0.0086\,\mathrm{Cl}\,,$$

$$pK_W = 14.170 - 0.1517\sqrt[3]{\mathrm{Cl}} + 0.0083\,\mathrm{Cl} + 0.035\,(20.0 - T)\,.$$

Lastly, the total concentration of boric acid is

$$[\Sigma H_3BO_3] = 0.0000221 \times \text{chlorosity}\,.$$

Substituting the values for the dissociation constants and the total boric acid in the four basic equations and using the measured values of $[\Sigma CO_2]$ and pH, the concentrations of $[HCO_3^-]$, $[CO_3^=]$, $[H_2CO_3]$, and $[H_2BO_3^-]$ were computed for each sample collected from the basin. A partial check of the computations was made using the relationship

$$[\Sigma CO_2] = [HCO_3^-] + [CO_3^=] + [H_2CO_3]\,.$$

It should be noted that nowhere has alkalinity, $[A]$, been used; and since

$$[A] = [HCO_3^-] + 2\,[CO_3^=] + [H_2BO_3^-]\,,$$

this offers a method of checking both the analyses of the water samples and the computations based on them. It was found, using this equation, that the computed and measured alkalinities of the twenty-two samples studied agreed within 6 per cent in all cases and averaged 2 per cent. In order to base subsequent computations of calcium on the measured $[A]$, as well as on the measured pH and $[\Sigma CO_2]$, the final alkalinity was taken as the average of the measured and the computed values, and $[HCO_3^-]$, $[CO_2^=]$, and $[H_2BO_3^-]$ were adjusted in the same proportions as computed.

The concentrations of the anions combined with calcium having been determined, the concentration of Ca^{++} in milligrams per liter was computed, with the results shown in Figure 13. From this

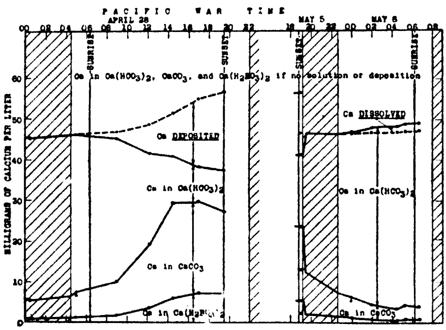

FIG. 13.—Diurnal variation in concentration of calcium combined with carbonate, bicarbonate, and borate ions in the water of the basin of Fig. 5. The dashed line indicates the concentration of this calcium if no solution or deposition occurred. Cross-hatching indicates flooding of basin at high tide.

diagram it appears that during the daytime, when $[\Sigma CO_2]$ is lowest, the calcium is combined chiefly as $CaCO_3$. For the conditions prevailing in the afternoon, only about one-fourth of the calcium is combined as $Ca(HCO_3)_2$; and, because of the high pH at that time, there is a nearly equal amount of calcium in $Ca(H_2BO_3)_2$. During the nighttime, the situation is very different, for then, when $[\Sigma CO_2]$ is highest, nearly all the calcium exists as $Ca(HCO_3)_2$, and only small quantities of $CaCO_3$ and $Ca(H_2BO_3)_2$ are present. It should be noted from Figure 13 that the solid line forming the top boundary of Ca^{++} in $Ca(HCO_3)_2$ also

represents the total concentration in the water of calcium combined with all carbonic and boric acid components.

In order to determine whether calcium is deposited from the water or dissolved from the rock, it is necessary to compute the concentration of calcium *available* for distribution between carbonate, bicarbonate, and borate anions. As the tide receded after having flooded the basins, it left them filled with water of normal chlorinity. After the pool was exposed for a time during low tide, evaporation proceeded, with resulting concentration of the salts in the water. If no deposition of salts occurred, the chlorinity serves as an index of the increased concentration because the water is undersaturated with chlorides. Therefore, by adjusting the concentration of calcium at the time the basin was first exposed above the retreating tide by an amount proportional to the increase of chlorinity, the total concentration of calcium in the water available at a later time for combination with carbonic and boric acid components may be determined. The diurnal variation of this quantity is shown by the dashed line of Figure 13.

Decision as to whether deposition or solution of $CaCO_3$ occurs can readily be made from the relationships of Figure 13 by comparing the concentration of calcium available in the water with the concentration of calcium actually combined with the carbonic and boric acid components. In the afternoon there was available more calcium, which must be combined with carbonic or boric acid components, than the conditions of high *p*H and high temperature permitted the water to retain. The excess was precipitated. In this series of measurements the amount deposited was about one-third of the total, or 20 mg. per liter of water. During the night the reverse was true, for, while the concentration of calcium originally available in the water increased slightly because of evaporation, the amount actually present showed a greater increase. The additional calcium presumably was dissolved from the rock basin.

One or two other factors should also be considered. The estimate of available calcium was based on the assumption that no Cl^- had been deposited; however, if some NaCl crystallized at the edge of the basin the amount of evaporation, as indicated by chlorinity of the water, would be too low. As a result, even more calcium may have been available during the daytime than is indicated, with resulting greater precipitation of $CaCO_3$. No salt was noted, however, on the day that the water samples were collected. This correction could not have applied to the night series because of the lower temperature and the fact that the chlorinity increased only very slightly. Another circumstance may have caused an apparently too-high concentration of calcium in solution during the day series. If the reactions leading to precipitation were sluggish, so that the water became supersaturated, or even if the precipitation did occur but in colloidal form, Figure 13 would still show the concentration of calcium present in the water but, given sufficient time with no further change of conditions, even more calcium would probably be deposited. That such conditions actually exist is shown by the fact that the ion-product of $[Ca^{++}] \times [CO_3^{=}]$ in the afternoon reached $6.35(10)^{-6}$. According to the most recent data,[37] the saturation value, or the solubility-product constant, when corrected by the usual factors for the

[37] J. C. Hindman, "Calcium Equilibria in Sea Water," Ph.D. thesis (Scripps Inst. Oceanog., 1942), p. 39.

prevailing temperature and chlorinity,[38] is about $0.90(10)^{-6}$. Thus, even though Figure 13 shows that some $CaCO_3$ had been deposited, the water was still seven fold supersaturated. During the night, on the other hand, the ion-product of $[Ca^{++}] \times [CO_3^{=}]$ reached a low value of $0.72(10)^{-6}$. For that temperature and chlorinity the solubility-product constant is about $1.14(10)^{-6}$, indicating that, although some new Ca^{++} has been obtained by solution of the rock cement, the water was only about 60 per cent saturated. Similar computations show that the sea water at the time it flooded the basins was almost exactly saturated, having an ion-product of about $1.10 (10)^{-6}$.

CONCLUSIONS

ORIGIN OF BASINS

Although this type of rock tide pool has been described by a number of writers, few have offered theories as to origin. In one of the earliest reports, Henkel[39] suggested that similar basins at Vancouver Island are due largely to pothole abrasion, but this origin is belied by the fact that her photographs show the basins to be shallow and broad, in contrast to the deep narrow pothole usually encountered. Moreover, at La Jolla the walls are fluted and have soft friable surfaces. Seldom may an abrasive rock tool be found within a basin.

Kuenen[40] ascribed basins found on Morotai and Wotop islands to deposition of sea salt through evaporation at the edge of a pool of water, thus indurating a circle of rock which was left as a raised rim by the faster abrasion of the less resistant rock inside and outside the pool. At La Jolla it was commonly observed that the visible salt incrusting the rim is dissolved by the first wave which floods over the basin. Moreover, many of the basins have no rim and therefore could not have had that origin. Kuenen also supposed that the basins are restricted to tropical areas, though they had been reported from Vancouver Island, Canada.

In a recent paper Wentworth[41] ascribed certain basins in Hawaii to solution, not by sea water, which is ordinarily saturated with $CaCO_3$, but by fresh water from rain or run-off. This explanation suffers serious drawbacks in southern California.

As a result of the rock and water analyses already discussed, the writer offers the following sequence of events in the basin formation. When a ledge of calcareous rock, or sandstone cemented by calcite, is covered by the waves or by spray at high tide but is partly dried off at low tide, small pools of water remain in initial depressions of the rock, such as joints, ripple marks, concretionary areas, etc. Various intertidal plants and animals become established. Although the sea water is about saturated with calcium when it first covers the ledge, various changes in water characteristics take place as a result of biological processes of the plants and animals. During the daytime, the plants use CO_2 in photosynthesis, thereby raising the pH and reducing the total CO_2 content of the water to the point where it can little more than balance the calcium as $CaCO_3$. As a result of the high temperature, high pH, and low CO_2 content, much of the $CaCO_3$ is precipitated. If evaporation continues, all the other salts may be deposited; but this rarely occurs except in the smallest

[38] Sverdrup, Johnson, and Fleming, *op. cit.*, pp. 206–7.

[39] *Op. cit.*

[40] *Op. cit.*

[41] *Op. cit.*

basins. The $CaCO_3$ deposited from the main part of the tide pool is only loosely attached to the rock bottom, and it is washed out by turbulent waves at the next high tide. If the rock surface between the pools dries out at low tide, much of the $CaCO_3$ is deposited on the capillary fringe of the pool, where it serves as an additional cement for the rock, thus strengthening the rim area so that abrasion and weathering proceed less rapidly than in the surrounding area, and a raised rim is eventually left by erosion of the less resistant surrounding rock.

FIG. 14.—Karstlike topography developed by continued formation of solution basins (January, 1944).

During the night a different process is dominant. In the absence of light the plants no longer use CO_2 in photosynthesis but instead give off CO_2 in respiration, as do the animals. The resulting increase of CO_2 above the normal content for sea water lowers the pH. The low temperature, low pH, and high CO_2 content cause the calcium of the water to be combined with bicarbonate ion. In this state, the water is unsaturated with calcium, so that some of the $CaCO_3$ of the rock cement is converted to $Ca(HCO_3)_2$ which dissolves in the water. Once the cement between the sand grains is removed, the grains themselves are easily loosened and carried away by the waves. Many of the sand grains are ingested by snails, which therefore constitute an agent of erosion. Since the animals are the chief donors of CO_2, solution is greatest where they are most abundant and a cavity in the basin wall results. As the basin deepens the cavities become elongate, forming the flutings, within which clusters of snails may be seen.

As time goes on, the basin becomes wider and deeper, until finally it coalesces with other basins or reaches a rock joint. In either case the water-level may be lowered, and sometimes the basin may be almost completely drained. Thereupon another, a second-generation basin, may form in the bottom of the first basin. Eventually, the continued formation of solution basins may result in considerable weathering of the coastal rocks. Locally, it may even be the dominant process causing retreat of the coast (Fig. 14).

A similar process may be instrumental in the formation of some kinds of stone-lace (Fig. 15), for many small cavities in ledges or boulders are filled with snails and contain a small amount of water found to have a low pH. Stone-lace and solution basins on the top and upper sides of boulders near the Scripps Institution of Oceanography are sharp and well defined, but on the bottoms the basins are few, are weathered, and are partly obliterated. This probably indicates a change in the position of some boulders, probably resulting from exceptionally severe storm waves.

It is of interest to know whether basin-forming processes have an annual, as well as a diurnal, cycle. Most of the water analyses were made in April and May; but limited data collected in November, December, and August indicate that deposition during the day and solution during the night characterize all seasons at La Jolla. While plants are less abundant

in the pools during the summer, deposition continues because of the greater amount of evaporation. It is possible that solution is somewhat more rapid during the winter, when plants and animals are more abundant, with resulting greater contribution of CO_2 by respiration at night.

The general scarcity of these features around the coast of the United States is understandable when the character of the coast is considered. In New England the coast consists of noncalcareous igneous and metamorphic rocks. Most of the rest of the coast bordering the Atlantic Ocean and the Gulf of Mexico is sand beach. The main exception is in the vicinity of Key West, where there are coral reefs and where limited observations by the author showed the presence of a few solution basins. Rocks of the coast bordering the Pacific Ocean consist largely of volcanics; but locally there are outcrops of calcareous sandstones and, at least in La Jolla, the sandstone contains numerous solution basins. Wider distribution elsewhere is shown by the fact that basins have been reported in the literature, or the writer has seen them, at Bermuda, Puerto Rico, Cedros Island in Mexico, Vancouver Island in Canada, the Hawaiian Islands, Morotai Island, Wotop Island, and Ulithi Atoll.

RATE OF FORMATION

Though estimates of the rate of formation of the basins must be based on several assumptions and are therefore subject to considerable error, it is believed that estimates of the correct order of magnitude can be made, which may be of some interest. If the rate of solution of the rock is constant and is correctly indicated in Figure 13 as 0.0020 gm. of Ca^{++} per liter per night, then during an entire year 0.0025 gm. of Ca^{++}, or 0.0062 gm. of $CaCO_3$, is removed per square centimeter of the basin area. Since the rock contains about 8 per cent $CaCO_3$, the total amount of rock dissolved or uncemented is 0.075 gm. per square centimeter per year. The uncemented rock grains are removed by waves and by the snails feeding on blue-green algae. A single measurement of the quantity of rock excreted in one day by the snails from the basins was 0.311 gm., or 0.000062 gm. per square centimeter of the basin. This quantity is 0.022 gm. per year, about one-third the amount dissolved and uncemented, the remainder presumably being removed by wave action.

FIG. 15.—Stone-lace in a boulder near the Scripps Institution of Oceanography. There is a cluster of snails in each of the small cavities (January, 1944).

The removal of rock at the rate of 0.075 gm. per square centimeter per year corresponds to a deepening of about 0.030 cm. per year. Therefore, at the present stage of development of the basin, about 33 years would be required to deepen it 1 cm. Since the average depth below the top of the rim is 5 cm., the time required to develop the basin would have been of the order of 165 years. In the early stages the basin probably deepened more slowly, so that its total age probably exceeds 200 years. In many of the areas studied, some basins are deeper

than 25 cm., and there are numerous indications of previous generations of basins. It is, therefore, impossible to estimate the date when basin formation in these areas first began.

That an age of 200 years is not unduly great is shown by a comparison of some of the basins with photographs taken about 40 years ago. The changes are relatively insignificant and may have been caused by people walking on the basins.

ACKNOWLEDGMENTS.—Grateful acknowledgment is due many members of the staff of the Scripps Institution of Oceanography for their interest and help: Dr. E. G. Moberg, who made available chemical equipment for water analyses; Dr. C. E. ZoBell and Mr. Gregory Jankowsky, who furnished a pH meter and also made some measurements themselves; Dr. W. R. Coe, who examined the intestinal content of snails collected from the pools; Professor W. E. Allen, who examined the plankton in water from the pools; and Dr. Denis L. Fox and others, who made many helpful suggestions. It is also a pleasure to acknowledge the assistance given by Dr. R. H. Fleming, who helped interpret the chemical analyses; Dr. E. Yale Dawson, who identified the algae collected from the pools; and Mr. Edwin Bushman, who assisted in the early part of the geological investigation.

MIOCENE SUBMARINE DISTURBANCES OF STRATA IN NORTHERN ITALY

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ABSTRACT

In the Apennines, near Florence, our colleague, J. W. R. Brueren, observed remarkable intraformational structures in Miocene strata, one of which was described in 1941. In the present paper an attempt is made to give another explanation and a more detailed description of this example. The structures originated from flowage of an unconsolidated sand layer at the top of a series of marly and sandy deposits, causing deformation of underlying strata. Differential burden due to initial concentration of sand in lenses was responsible. In the literature, only two comparable examples were to be found.

In the Turin Hills, which must be considered as the northwestern end of the Apennines, we discovered another instance of disturbed stratification. In this case the folding resulted from a sliding of rather consolidated strata in the frontal region of a delta, the development of which may be advantageously studied in the region investigated.

A few notes on other kinds of disturbed stratification in the Turin Tertiary are added. The author made an attempt to compile all available data concerning sliding and flowing structures; but, since the results are rather unsatisfactory, he refers here only briefly to the many cases described in the literature.

INTRODUCTION

In 1937 the author started detailed geological investigation of the Tertiary hills east of Turin in northwestern Italy (Piemonte) which are famous for their enormous yield of fossil material and their peculiar structure, showing three main directions of folding. An unusual example of subaqueous sliding was discovered and is here described. At the same time our colleague, J. W. R. Brueren, made observations on disturbances in Miocene strata in another, tectonically very important, part of the Apennines near Florence.[1] Both examples, mentioned briefly in our papers of 1941,[2] are now discussed more amply.

[1] *De geologie van een deel der Etruskische Apennijnen tusschen Firenze en Bologna* (University of Leyden thesis) (Assen: Van Gorkum Co., 1941).

[2] C. Beets, *De geologie van het westelijk deel van het Heuvelland van Monferrato tusschen Turijn en Murisengo* (University of Leyden thesis) (Assen: Van Gorkum Co., 1941); "Die Geologie des westlichen Teiles der Berge von Monferrato zwischen Turin und Murisengo," *Leidsche Geol. Meded.*, Vol. XII (1941), pp. 195–250 (an extensive summary of the foregoing paper).

Literature on sliding structures, only recently available to the writer, has aided in the interpretation of these forms. Though the last decenniums especially have yielded many observations on subaqueous disturbances of strata, we still lack sufficient data on recent examples, so the actuality principle, which must be handled very carefully, cannot be invoked to support our conclusion.[3] The deposits of recent types of geosynclinal basins cannot be studied *in situ*, which, of course, would be of the greatest value in the interpretation of strata. We must also bear in mind the possibility of convergence, i.e., identical final products may result from various causes, and the same cause may lead to different products.[4]

[3] E. Kayser, "Der Grundsatz des Aktualismus in der Geologie," *Zeitschr. d. D. Geol. Ges.*, Vol. LXXXIII (1931), pp. 389–407; K. Andree, "Rezente und fossile Sedimente," *Geol. Rundschau*, Vol. XXIX (1938), pp. 147–67; *idem.*, "Die wichtigsten Faktoren der marinen Sedimentbildung jetzt und einst," *Geol. Archiv.*, Vol. II (1923), vi (a hardly attainable, nearly uncited, paper).

[4] Kayser, p. 405 of ftn. 3.

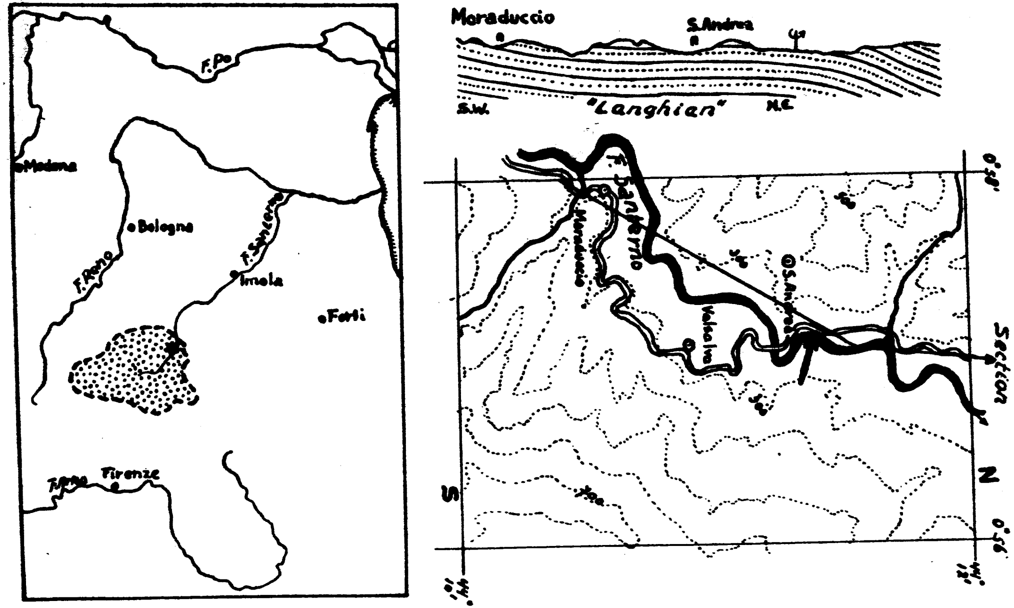

FIG. 1.—The small-scale map (about 1:2,600,000) on the left indicates the area studied by Brueren; the asterisk, the location of the photograph of Fig. 2. Map and section on the right represent Part M.6 of Brueren's geologic map and part of his Section VII, respectively (scale about 1:64,000). The map shows a "Langhian" landscape. The photograph of Fig. 2 was made near San Andrea, on the left bank of the Santerno River (arrow indicates locality and direction of view).

In the following pages the examples described in the literature are discussed very briefly.

SUBMARINE FLOWAGE IN "LANGHIAN" STRATA, NORTHEAST OF FLORENCE

In the area studied by Brueren[5] in the Etruscan Apennines (left part of Fig. 1), he discovered many examples of disturbances of "Langhian" (Burdigalian) and Helvetian strata. A fine example is given in our Figure 2, representing Brueren's Figure 2 facing page 65 of his paper. The photograph was made by G. G. Wissema, who kindly communicated some details. To him and to Brueren we express our indebtedness.

Brueren published the following explanation, here translated and edited with our comments (in brackets):

In an undisturbed series of sandstones and marls, we observe two irregularly limited sandstone layers separated by an undulating marl layer. The lower sand layer is divided into pieces showing undisturbed [?] surface of contact with underlying marl, but its upper surface is undulated. The upper sandstone has a flat top surface, but now its lower surface is undulated in all directions. The deepest parts of the upper layer correspond with those places where portions of the lower sand layer have disappeared [or were thinned out].

The marl between the sands has functioned as a sliding [lubricating] layer. During the sliding action the lower sand layer was partly involved. On the places where we now observe sand tumors, the sediment was accumulated. The marl layer was folded [flowed] over the sand waves, forming depressions between them. We observe a lens-shaped portion of the lower sandstone lying in a marly matrix, found back above the lower sand lens in the right part of the photo.

FIG. 2.—Showing result of subaqueous movement in "Langhian" strata near San Andrea (cf. Fig. 1). The breadth of the whole disturbed part of the exposed section does not exceed 16 meters, about twice the length covered by the photograph. (Photograph by G. G. Wissema.)

In the depressions of the marl, sand masses of the upper layer accumulated. At the left we observe the marl mud having made its way through a sand lens, causing the irregular sand accumulation [in our opinion, it is a normally shaped portion of the whole sand lens] at the right of the intrusion. This accumulation and the big lens about in the middle of the photo [according to Wissema, the breadth of this lens is 2.40 meters] are joined by a slightly waved but rather regular sand layer showing a slight variation of thickness. Although this layer was somewhat thicker in its original state, it may give us an idea of the situation before the sliding action.[6]

It is clear that the disturbed sandy and marly deposits must have remained nearly unconsolidated until the beginning of the movement, which must be

[5] See ftn. 1.

[6] P. 59 of ftn. 1.

called a "flowage of quicksand" rather than a "sliding action."

Brueren has described both the Langhian and the Helvetian strata in this area as chiefly fine-grained, chalky sandstone layers, alternating with marly sediments, probably representing shelf deposits. In the Langhian series we may now and then observe big limestone blocks, which are only known from the near-by "Argille scagliose."[7] These peculiar formations play the same part in the tectonic history of the Apennines as the salt series in dome structures and allied phenomena. In the northwestern part of the area studied by Brueren the "Argille scagliose" and Eocene strata formed a land area which supplied the enormous amount of clastics of the Miocene series, including limestone blocks from the "Argille scagliose" formation. In the northern part of the area, quiet sedimentation took place.

It is therefore obvious that the flowing and, in general, the lateral movements near San Andrea occurred on the eastern submarine slope of the land area mentioned above.

Disturbances of this type are not common, according to the literature. Flowing of sandy deposits containing gastropods may produce interesting results, according to Krejci-Graf.[8] Flow structures, such as those described by Hadding,[9] are not comparable with Brueren's example, and it is difficult to say whether the flowage near San Andrea was quick or slow. Subaerial flowage, discussed by Kieslinger,[10] also results in different structures.

At San Andrea the sand masses do not show any stratification, and no cleavage is developed—thus indicating, presumably, an unconsolidated mass during the movements. Accordingly, we may conclude that the original stratification has been totally obliterated. We therefore use the term "flowage" instead of "sliding," in accordance with Richter's use of the term.[11]

Lippert, who has divided the sliding phenomena according to mode of movement and result, has also discussed examples of "downward movements accompanied by change of structure" (*Gekreich und Gefliess*), combined with "movements without change of structure" (*Rutschung und Gleitung*) (cf., e.g., Lippert's Figs. 2 and 3). His Figure 2, at first sight, greatly resembles Brueren's figure, but Lippert explains the structure by the slackening of speed of a gliding mass of rather consolidated tuffs and clays, accompanied by intrusion of mud —which had served as a lubricant—into the fold and fault structures developed. In our case the circumstances were different from those assumed by Lippert, and we, therefore, shall try to explain anew the structure described by Brueren.

As pointed out above, both the sandy layers and the intermediate marl must have been practically unconsolidated at the beginning of the downward movement. They were in the state of a semiliquid mass. By an unknown accident this mass flowed over undisturbed strata,

[7] *Ibid.*, pp. 58, 198.

[8] K. Krejci-Graf, "Senkrechte Regelung von Schneckengehäusen," *Senckenbergiana*, Vol. XIV (1932), pp. 295–99.

[9] A. Hadding, "On Subaqueous Slides," *Geol. For. Stockholm Forh.*, Vol. LIII (1931), pp. 377–93.

[10] A. Kieslinger, "Eine boden-physikalische Betrachtung der Gefliess-Marken (Fliesswülste)," *Senckenbergiana*, Vol. XIX (1937), pp. 127–38.

[11] H. Lippert, "Gleit-Faltung in subaquatischem und subaerischem Gestein," *Senckenbergiana*, Vol. XIX (1937), pp. 355–75 (p. 357: "Gefliess").

of which only the upper layers were slightly involved and folded (left and right parts of Fig. 2). Apparently the uppermost quicksand layer began to move differentially upon the marly mud. The development of a waved surface of contact below the drift sand resulted through the operation of the well-known principle of Helmholz (1888): A sinuous surface of contact will arise between moving fluids—in this case suspensions—of different specific weight. This action was promoted by the specifically heaviest layer lying at the top of the series.

Sand accumulated in the regularly developing wave depressions. This increased their burden in contrast to the "anticlinal" waves, where no sand could accumulate because the sand suspension flowed down their flanks into the depressions. In consequence of the growing sand accumulations, the intermediate mud and the lower sand layer (especially the latter) were pressed aside below the added overburden and were concentrated at places of least pressure. This process continued until movement stopped.

The lower sand layer was slightly consolidated, as may be proved by the sand lens at the right in Figure 2. This is a portion of the lower sand layer, which was enclosed by the intermediate mud and moved to the nearest place of least burden, where another part of the sand layer was deposited in the second lens. It must be borne in mind that the superposed lens might have originated from a marly intrusion, separating one larger lens into two portions.

The superposed undisturbed strata must have been absent at the time of flowage, as is proved by the marly intrusion on the sand lens at the left. The mud even extruded; but, as there is no trace of disturbed stratification above, the extruded mud must have been washed by the sea. It is, of course, a rather mysterious intrusion, for we should expect it at a place of low pressure, between the sand lenses of the upper layer. Most probably, however, rupture was caused by the sinking of the heavy sand lens to the bottom of the mud. This reminds us of the basic intrusions of "pietre verde" in bottom strata of several geosynclines. Note the beginning of the intrusion outside the center of the sand accumulation and its radial direction. Further, it is notable that the different mediums, sand and clay suspensions, did not undergo striking mixture during the flowage.

Lippert[12] has pointed to the existence of a so-called "whirl-zone" (*Aufwirbelungszone*) in examples of subaqueous sliding, and perhaps the structures near San Andrea also developed a whirl-zone above, for the contact between the upper sand layer and the superposed marls seems to be less sharp than the boundary between sand and the intermediate marl layer (cf. right part of Fig. 2).

It is not easy to determine the cause of the flowage of the uppermost drift-sand, which started the whole action. The general character of the stratification in this area does not support the postulate of a delta with steepening slopes. The following are a few suggestions:

1. Excessive local deposition and removal of support through erosion of adjacent deposits.

2. Disproportional load, in this case on the prolongation of the disturbed mass, for we have already affirmed the absence of deposits immediately above the drift sand at the spot observed. Also, the structure now developed differs much

[12] *Ibid.*, p. 361.

from the examples of intraformational disturbance discussed by E. M. Kindle.[13]

3. In the submarine flank of the Miocene land area mentioned above, quicksand might have originated through expulsion of water from dipping strata.

4. The best explanation which can be given at the moment seems to be the following: Clay sediments may undergo considerable compaction, as is well known. Now compaction, without real consolidation of the "intermediate" marly mud, due to increasing sandy deposits above, will be accompanied by expulsion of water which will rise into the superposed sand layer. A slight inclination of the sea bottom would suffice for flowing, and balance might be disturbed by slight downward movements common to sedimentary basins, giving an increase of inclination. The symmetry of the sand lenses seems to indicate flowage from the sides of a very slight sea-floor depression toward its center. This interpretation seems most likely, but we must await further detailed investigation of the transition between the disturbed strata and undisturbed equivalents near by. The stratification of the intermediate marl is a result of compaction. It certainly does not represent any initial stratification before the flowage.

R. H. Sorby[14] and S. M. K. Henderson[15] have described phenomena resembling Brueren's example to a certain extent, although the structures are developed on a scale twenty-five to thirty times smaller. Sorby discussed wavelike tuffaceous layers with normal lower surface. The waves are overthrown in one direction like breakers, indicating the direction of currents. They are covered with other tuffaceous deposits. According to Sorby, the breakers originated from disturbance of semiliquid mud on the sea bottom, washed by a current of water (started by a volcanic disturbance), which carried fresh, coarser ashes. Parts of the breakers were involved by the flowing mass. In our opinion we must also bear in mind the possibility of heavy rains on ash deposits of volcanic slopes developing suspensions, which, indeed, might act upon the fresh deposits of the submarine slope in the above-mentioned way.

Henderson described the result of a sand suspension flowing over somewhat consolidated mud. These structures closely resemble those studied by Sorby. Henderson attributed the disturbances to seismic causes connected with the development of a geosyncline. As is pointed out above, the same might apply to Brueren's case. In many respects Henderson's example may be best compared with Brueren's.

HELVETIAN SUBMARINE SLIDING IN THE TURIN HILLS (MONFERRATO)

a) In the Turin Tertiary the author discovered another example of subaqueous movement of strata near the picturesque village of Casalborgone (Fig. 3, *b*) about 20 km. east-northeast of Turin (cf. Fig. 6). This disturbance was briefly discussed in 1941.[16] Figure 4 of the present paper shows the section

[13] "Deformation of Unconsolidated Beds in Nova Scotia and Southern Ontario," *Bull. Geol. Soc. Amer.*, Vol. XXVIII (1917), pp. 323–34.

[14] "An Application of Quantitative Methods to the Study of Rocks," *Quart. Jour. Geol. Soc. London*, Vol. LXIV (1908), pp. 197–233 (cf. pp. 196–97, Pl. 14).

[15] "Ordovician Submarine Disturbances in the Girvan District," *Trans. Roy. Soc. Edinburgh*, Vol. LVIII (1935), pp. 487–509 (cf. p. 502, Pl. 2, Fig. 3).

[16] Beets, *De geologie van het westelijk deel van het Heuvelland van Monferrato tusschen Turijn en Murisengo*, pp. 60, 88–89, Pl. 2, Fig. 1; "Die Geologie des westlichen Teiles der Berge von Monferrato zwischen Turin und Murisengo," pp. 219 (n. 52), 237 (Fig. 9), 238.

which may be studied well in the steep slope north of the main road from Airali to Casalborgone (cf. Figs. 3, 5, and 6). The simple geology of this area may be described as follows: We are here about in the center of the shallow and tectonically very simple syncline of Casalborgone, in a sandy series of marine Helvetian, which shows, horizontally as well as vertically, considerable lithologic variation. Near the place of the photo (Fig. 4), in the flanks of the almost isolated hill of Casalborgone, we observe a lower, undisturbed series of alternating sands and marls (*s-m* in the next pages). This series is covered by a relatively thick sand layer and other marly sands as well as by irregularly intercalated marl layers. The disturbed strata did not undergo tectonic folding, as they are in an almost unfolded part of the syncline. The lower boundary of the folded series must represent a gliding horizon; the upper surface is a slightly wavy erosion unconformity.

The explanation of the disturbance is that a certain part of the upper layers of a series of sand and marl sediments, deposited on a submarine slope, underwent a downward sliding movement. The sliding plane may either have developed mechanically or, more probably, was the

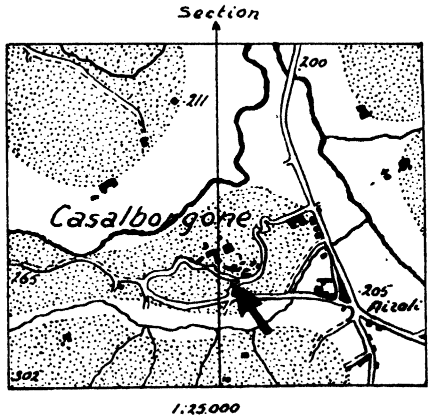

FIG. 3*a*.—The center of the syncline of Casalborgone in the Turin Hills (*dotted:* Helvetian deposits; *white:* alluvial Quaternary). The arrow locates Fig. 4 and the direction of the photograph.

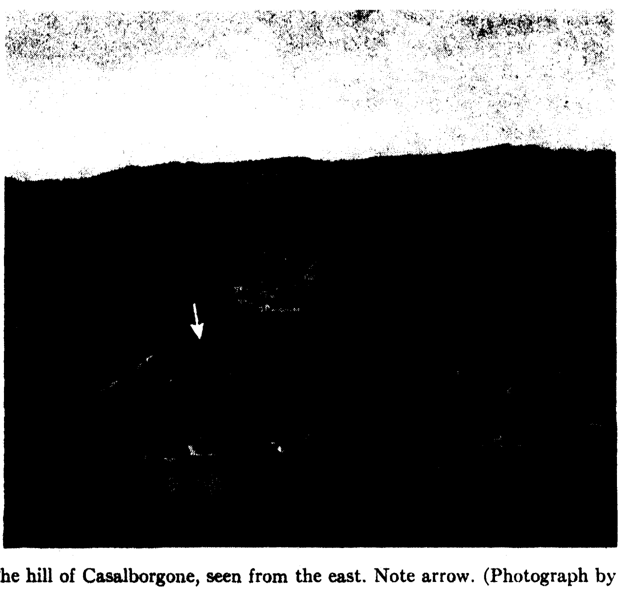

FIG. 3*b*.—The hill of Casalborgone, seen from the east. Note arrow. (Photograph by the author.)

surface of the sediments in front of the sliding mass (cf. Twenhofel's idea).[17] The folds apparently originated from stowage, combined with slackening speed of the sliding mass. We do not know at present whether the folding is everywhere slight, but we may suppose that the front of the slide developed some beveled the folds. The boundary certainly does not represent a tectonic thrust plane, which, moreover, could not be expected in this simple and shallow syncline. This erosion was a submarine one, as the sliding series moved toward a deeper part of the sea floor. Subaerial erosion is very improbable. According to

FIG. 4.—Subaqueous sliding in Helvetian strata of Casalborgone in the Turin Hills, Monferrato, Piedmont. (Photograph by the author.)

"breakers" against the underlying strata which acted as a brake. According to the strike of the folded strata (northeast-southwest), the sliding was directed to the southeast or the northwest. Other features point to the former direction.

The nature of the surface of contact between the folded and unfolded superposed strata indicates that the sliding mass has been subject to erosion, which the nature of the strata in the neighborhood and the Helvetian sedimentation in general, there is no evidence for a sudden fall and rise of the sea-level,

This erosion seems to contradict the enormous deposition of Alpine clastics in the Turin basin during Helvetian time; but here there was only a very short period of erosion, which was connected intimately with the sliding itself. It is explained by an intensive turbulent action of the sea water during the sliding, accompanied by the rise of a suspen-

[17] W. H. Twenhofel, *Treatise on Sedimentation* (2d ed.; Baltimore: Williams & Wilkins Co., 1932), p. 742, Fig. 109.

sion caused by the whirling of unconsolidated sediments. From frontal to posterior part of the slide the erosion of its surface increased. A suspension of this kind will act with strong erosive force,[18] and a second suspension will serve as a lubricant below the sliding mass.

A "whirl-zone," the deposition of the erosive suspended material after movement had ceased, should have been developed chiefly behind the sliding mass and afterward have been partly eroded during the transport of the sand grains of the first superposed layer. So the present contact between folded and overlying unfolded strata may be considered the result of two erosive actions separated by a short period of deposition. Perhaps the whole whirl-zone was eroded during the second erosion, for we could not verify it.

In contrast to the above-mentioned phenomenon, we observe in the present case an increase in number and thickness of strata[19] at the very spot of the sliding mass, while somewhere in the neighborhood a decrease in number of strata must exist (not observed).

b) When trying to explain the subaqueous "solifluction,"[20] we must consider the possible cause. Unlike most cases of sliding, this example furnishes us with sufficient proof in the development of the sedimentary basin of Casalborgone.[21] We therefore give a brief synopsis of the Helvetian sedimentation in the Turin Basin.[22]

The Helvetian deposition followed after the quiet sedimentation of the Langhian stage. In the western part of the Turin Basin it is characterized by the deposition of an enormous amount of coarse-grained clastics, derived from the huge Pennine chain, which formed a land area during the whole Tertiary. In the

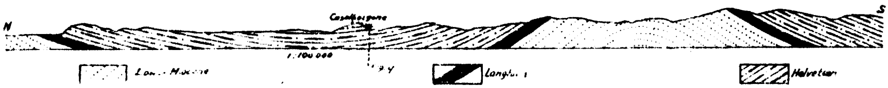

Fig. 5.—Section through the syncline of Casalborgone. The asterisk indicates the locality of Fig. 4

[18] As the sliding mass was folded, that is to say at the spot figured here, it was easy to recognize an erosion surface. But we saw the sharp contact first at another place where pseudo-concordance was observed. There we could only think of erosion in a sense which must be called normal, for, as we pointed out in 1942, in accordance with other investigators (Winkler, cited below), we often must consider sharp boundaries between concordant strata as the result of erosive forces. In the above-mentioned case the contact was so sharp that we followed it and soon discovered the unconformity. Cf. R. Brinkmann, "Über die Schichtung und ihre Bedingungen," *Fortschr. Geol. u. Pal.*, Vol. XI (1932), pp. 187–219; A. Kumm, "Schicht, Bank, Lager," *Geol. Rundschau*, Vol. XXIII A (1932), pp. 186–200; C. Beets, "Das Schichtungsproblem, ein Beitrag aus den Turiner Bergen ('Colli Torinesi')," *Leidsche Geol. Meded.*, Vol. XIII (1942), pp. 39–62.

[19] This increase results, according to Heim, from (1) direct superposition by the sliding mass and (2) deposition of the suspension which arises from the sliding (cf. A. Heim, "Über submarine Denudation und chemische Sedimente," *Geol. Rundschau*, Vol. XV [1924], pp. 1–47 [cf. p. 21]).

[20] Solifluction: see Andersson. Heim (see ftn. 19) introduced the term "subsolifluction" for phenomena in the sense of the one discussed here, but Schaffer did not appreciate this term. Cf. J. G. Andersson, "Solifluction, a Component of Subaerial Denudation," *Jour. Geol.*, Vol. XIV (1906), pp. 91–112; F. X. Schaffer, "Über subaquatische Rutschungen," *Centrallbl. f. Min., etc.* (1916), pp. 22–24.

[21] "Auch die Gesteine sind abhängig von ihrer Umwelt und nur dann genetisch zu erklären, wenn man sie nich nur für sich, sondern im Rahmen von Abtragungsgebiet, Transportbahn und Sedimentationsraum betrachtet, alle Eigenschaften der einzelnen betrachtend" (Kayser, pp. 405–6 of ftn. 3).

[22] Beets, ftn. 2.

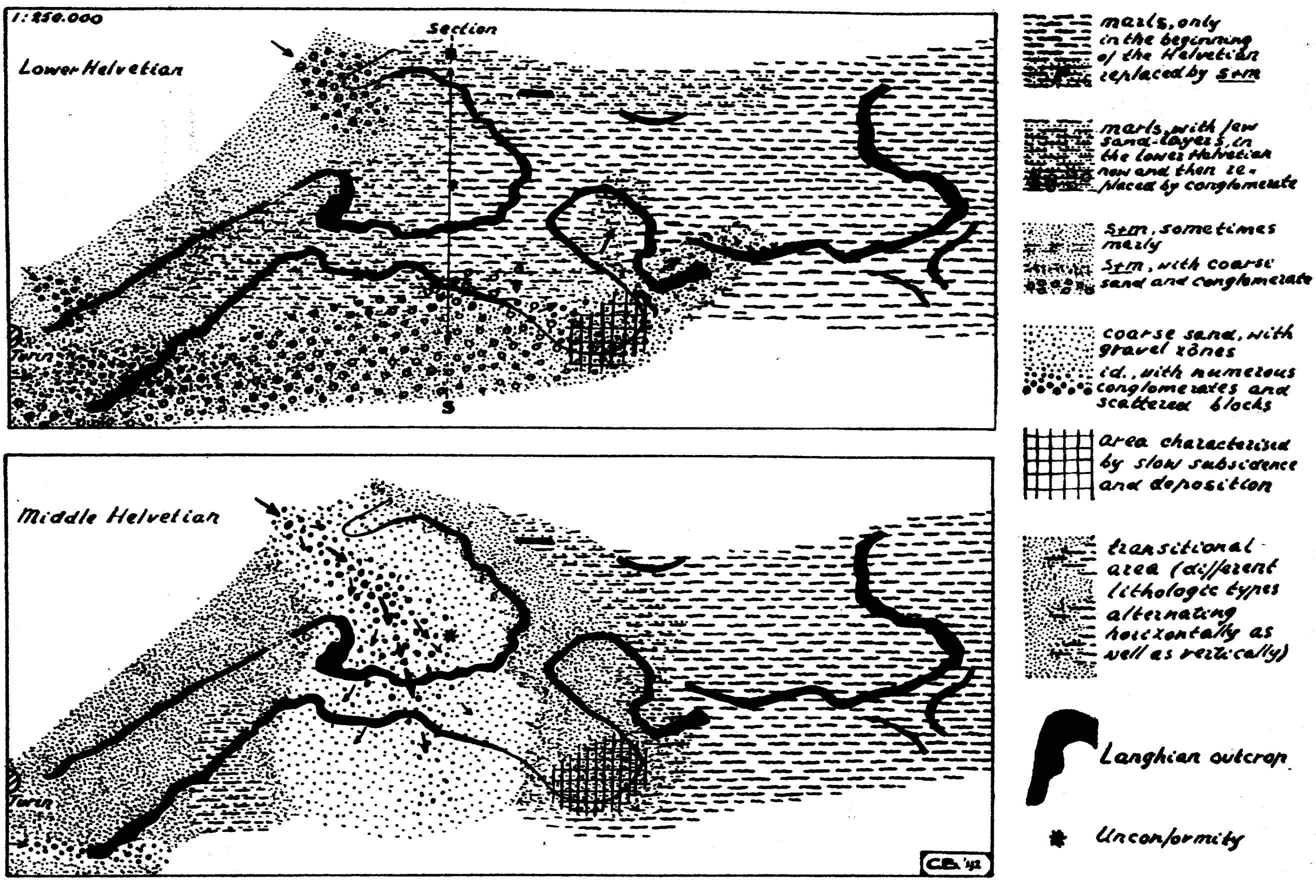

FIG. 6.—Summary of the spreading of several lithologic types in the Turin basin during part of the Helvetian stage. The maps represent the western part (Turin Hills) of Monferrato. The Langhian outcrops were used as basis for the paleogeography. The section indicated on the map for Lower Helvetian is magnified in Fig. 5 (Sec. 19 of the papers by the author, 1941). The asterisk agrees with the one in Fig. 5.

lower Helvetian (cf. Fig. 6) large parts of the basin were covered with marly sediments. Over a southern shallow zone, which already existed in Lower Miocene and Langhian, coarse deposits accumulated. In the eastern part of this zone we observe an oval structure, the so-called "dome of Serra," where the Mesozoic "Argille scagliose" was rising regularly ("diapyrous"), causing slow subsidence and sedimentation. In a short period between the two which are mapped, the sedimentation of the southern strip was replaced by that of a series of *s-m* deposits.

In the Middle Helvetian (Fig. 6, below) this zone was again occupied by coarse-grained sedimentation, but now only in the west. It must be emphasized that the dome of Serra played the same part before the Helvetian (post-Eocene) and after it, until Pliocene time at least.

The delta built in the northwestern part of the basin will stand in direct connection with the slide near Casalborgone. This delta had reached the mapped area in Lower Miocene time. In the following Langhian stage it was relatively inactive, but in the Lower Helvetian coarse deposition went on. Around the front of the delta *s-m* deposits and marls were laid down.

In a somewhat younger period (not mapped), the delta deposited finer sediments, namely, *s-m*, in accordance with the finer sedimentation in the southern zone (see above). Soon the coarser deposition reappeared, and the delta tongue, the main transport zone, was shifted somewhat to the south. At about the same time the *s-m* deposits of Casalborgone were laid down as part of a large areal accumulation in front of the delta.

This delta was characterized by rapid deposition, and it spread particularly in a southeastern and southern direction. Figure 6 shows the delta in extreme development. Enormous amounts of coarse sand deposits, gravel, and conglomeratic zones were laid down, and also numerous scattered huge blocks, which suggest the existence of large "mud" flows (streams of mud, sand, gravel, pebbles, and blocks),[23] like recent examples, fan-shaped before a relatively narrow transport zone.

This short summary of the Helvetian sedimentation, based on detailed investigation of the lithologic variation in the Turin Basin, may suffice.

If we compare the situation of the sliding mass with the development of the delta in space and time, it is permissible to assume close connection between them. We may accept the following explanation: The *s-m* deposits of Casalborgone belonged to the submarine frontal slopes of the delta, which advanced southeastward and southward. At Casalborgone first marls, afterward *s-m*, coarse sand, and coarser deltaic sediments, respectively, were deposited. The cause of the sliding[24] was probably only

[23] Twenhofel, pp. 93–94 and Figs. 6–7 of ftn. 17.

[24] We might suggest seismic causes, for these are known to play a part in recent ruptures of telegraph cables: cf. Milne and also Yamasaki. Aldinger does not like assuming seismic causes, as these cannot be proved in fossil examples. Occurrence of sliding is recognized in many tectonic processes (cf. Baldry, Brown, Marin, and Kuenen's summary).

Cf. J. Milne, "Sub-oceanic Changes," *Geogr. Jour.*, Vol. X (1897), pp. 129–46, 259–89; N. Yamasaki, "Physiographical Studies of the Great Earthquake of the Kwânto District, 1923," *Jour. Fac. Sci., Imp. Univ. Tokyo*, Sec. 2, Vol. II (1926), pp. 76–119; H. Aldinger, "Über die Entstehung der Kalkschiefer des oberen Weissen Jura von Nusplingen in Württemberg," *Centrallbl. f. Minn., etc.* (1930), B, pp. 257–67 (cf. p. 264); R. A. Baldry, "The Clay Pebble Bed of Ancon, Ecuador," *Geol. Mag.*, Vol. LXIX (1932), pp. 45–46; R. A. Baldry, "Slip-Planes and Breccia Zones in the Tertiary Rocks of Peru," *Quart. Jour. Geol. Soc. London*, Vol. XCIV (1938), pp. 347–58; C. B. Brown, "On a Theory of Gravitational Sliding Applied to the Tertiary of Ancon, Ecuador," *Quart. Jour. Geol.*

the creation of too steep an inclination through rapid sedimentation in the frontal part of the delta,[25] perhaps combined with one of the many subsidences of the sea bottom which are responsible for cyclic stratification of the sediments.[26] A labile part of the sediments slid down to deeper water.[27] As already stated, the slide moved in either a northwest or a southeast direction (according to the strike of the folded strata). The delta indicates sliding in a southeasterly direction.

We do not know the distance of the sliding movement, but apparently the deepest place in a shallow basin between the starting-point of the slide and the dome of Serra—which acted more as resistance against subsidence than as a real topographic rise—was at Casalborgone. It is impossible to reconstruct with any certainty the bathymetry of the Helvetian basin at the moment of sliding.[28] We know no more than that the sediments described were shelf deposits; but, from the distribution of gravels and conglomeratic zones,[29] we may suppose the coastal line to have been about over the small anticline northwest of Casalborgone. The distance from this coastline to Casalborgone would amount to 6 km. at the most. If we estimate the depth of the sea basin at 200 meters (max.), then the average inclination of the submarine delta-front would have been 3° at a rough estimate.

According to A. Heim[30] and Grabau, a slope of 4.4 per cent (2.5°) will suffice for sliding; but, according to Escher,[31] this figure is too low because of the complication of extra burden by buildings in the case of the recent Swiss lake slides discussed by Heim. He was of the opinion, however, that very small inclinations might suffice for sliding,[32] stimulated by increasing thickness of the labile strata.[33] On the other hand, the

Soc. London, Vol. XCIV (1938), pp. 359–68; R. Martin, *Leidsche Geol. Meded.*, Vol. VIII, pp. 55–154; Ph. H. Kuenen, "Geological Interpretation of the Bathymetric Results," *The Snellius Exped. 1929–30*, Vol. V (Geol. Res.), Part I (1935).

[25] A possibility suggested by Andree (cf. K. Andree, *Geologie des Meeresbodens*, Vol. II: *Bornträger* [1920], p. 272, and p. 262 of ftn. 6 [1923]); cf. p. 740 of ftn. 17.

[26] See Beets, ftn. 18.

[27] It may be added here that in many cases of strange combinations, either of lithologic or of faunistic character, subaqueous sliding is supposed to have played a part. Cf. Twenhofel, p. 740 of ftn. 17; Andree, p. 273 of ftn. 25; Kuenen, p. 71 of ftn. 24; and W. P. Woodring, *Carnegie Inst. Wash. Publ.*, Nos. 366, 385 (1925–28). Rutsch (*Eclogae geol. Helvetiae*, Vol. XXIV [1931], pp. 258–59) has disrupted Woodring's suppositions.

[28] Andree, p. 288 of ftn. 25.

[29] See geologic maps, Beets, ftn. 2.

[30] "Über rezente und fossile subaquatische Rutschungen und deren lithologische Bedeutung," *Neues Jahrb. f. Min., etc.* (1908), pp. 136–57.

[31] B. G. Escher, "Beschouwingen over het opvullingsmechanisme van diepzeeslenken," *Verhand. Geol. Mijnbouwk. Gen. v. Ned. en Koloniën, Geol. Ser.*, Vol. III (1916), pp. 79–88.

[32] Escher (see ftn. 31) and Horn accepted submarine sliding as an important agent in the accumulation of sediments in deep-sea depressions (inclinations 5°–20°, in most cases 4°–10°). Submarine slidings would explain peculiar alternation of bathyalic and neritic sediments. Arnold Heim (p. 21 of ftn. 19) suggests: "Wie gross muss daher erst die Bedeutung (of the slidings) sein für die riesigen Böschungen nach den Tiefseegräben, die bis zu 36° Steilheit erreichen." In 1941 (Beets, p. 238 of ftn. 2) we cited Heim's paper of 1924 incorrectly in connection with the Turin Basin, for Heim's conclusions did not apply to basins of the Turin type.

When considering cross-sections of sea basins, Kuenen (see ftn. 24) cannot accept Heim's view cited above. In exceptional cases only, neritic sediments would reach the great deeps. According to Kuenen, the few observations on sliding in fossil state are because of the rarity of the phenomenon. Cf. E. Horn, "Über die geologische Bedeutung der Tiefseegräben," *Geol. Rundschau*, Vol. V (1915), pp. 422–48.

[33] See Twenhofel, p. 741 of ftn. 17, and Kuenen, p. 71 (pp. 69–72) of ftn. 24.

data collected by the "Snellius" expedition have indicated that some sediments show surprising stability on steep slopes. As Kuenen has pointed out, marine sediments in general will attain a certain consolidation more quickly than will non-marine sediments. The slow deposition of the fine-grained sediments discussed by Kuenen would allow more time for consolidating processes than the rapid deposition of other deposits, before their inclination became sufficient for sliding. The inclinations mentioned by Kuenen are extremely high: 7°–34° for deposits of 1 meter in thickness in one of the very active seismic areas of the earth. Unfortunately, we cannot compare these data for fine-grained sediments with the conditions in the Turin case. On the other hand, Twenhofel[34] has cited high angles for subaqueous sandy deposits, collected by Miss Draper: 33°–43° (coarse sand) and 35°–38° (finer sand). And, furthermore, Kuenen has pointed out[35] that perhaps he observed only the stable lower portions of a much thicker series of strata, the upper portions having repeatedly slid away: "Our investigation therefore only proves the possibility of a certain amount of accumulation (1 m.) but does not exclude the possibility of slides, either sudden or gradual." From the data available we may conclude that more investigations of recent and fossil slides are needed before reliable comparisons can be made.

The partial consolidation of the sliding mass near Casalborgone is proved by the structures presented.[36] Consolidation is the first condition for development of the finest examples of disturbed strata.[37]

The final event which led to sliding is doubtful. It may have been seismic or only one of the supposed small subsidences. In the latter case we might expect many more slides in the Turin Tertiary, as in all basins with rapid deposition.[38] So Aldinger[39] seeks to explain sliding structures by referring to Klüpfel's well-known studies of Jurassic sediments, in which frequent rise and fall of sea-level played an important part. But neither elsewhere in the Helvetian basin of Casalborgone, which may be studied in numerous exposures, nor in other series in the Turin Basin did we observe slides comparable with that at Casalborgone. The sliding in the frontal part of the delta[40] might be exceptional.

OTHER CASES OF SOMEWHAT SIMILAR STRUCTURES

Although subaqueous slides in unconsolidated strata are likely to be overlooked in most cases, it is astonishing to note the variety of sliding structures ob-

[34] P. 604 of ftn. 17.

[35] P. 71 of ftn. 24.

[36] Escher (p. 80 of ftn. 31) has expressed the opinion that preservation of structure of sliding sediments is exceptional. Of course, this view applies in the first place to quick sliding actions over great distances, from the neritic regions to deep-sea basins.

[37] F. Hahn, "Untermeerische Gleitungen bei Trenton Falls (Nord-Amerika) und ihr Verhältnis zu ähnlichen Strömungsbildern," *Neues Jahrb. f. Min., etc.*, add. Vol. XXXVI (1912), pp. 1–41 (cf. p. 15).

[38] Hadding, p. 380 of ftn. 9.

[39] See ftn. 24.

[40] The reader will observe that the delta discussed does not agree with the usual textbook picture of delta structure. This is due, to a certain degree, to the special mudflow character of the supply in the Turin example. From time to time, in Lower and especially Middle Helvetian time, this delta reminds us of the Alpine "Wildbach" delta type. These fan-shaped accumulations of clastics on their part remind us of submarine volcanic slopes which show sliding as well (cf. Kuenen). See P. D. Trask, *Recent Marine Sediments: A Symposium* (London: Murbury, 1939); Ph. H. Kuenen, "Contributions to the Geology of the East Indies from the Snellius Expedition, Part I, Volcanoes," *Leidsche Geol. Meded.*, Vol. VII (1935), pp. 273–331.

served by a great number of authors. But we encountered no structures which might be compared directly with our delta slide. Aldinger[41] observed scale-like foldings in Jurassic strata of Württemberg. Bailey, Collet, and Field[42] described several intraformational conglomerates in Paleozoic rocks near Quebec, in close connection with tectonic lines. These phenomena and those mentioned by Bailey and Weir[43] in Kimmeridgian strata of East Sutherland are not comparable. The same applies to the interesting structures discovered by Musper[44] in the Padang Highlands, Sumatra; to slidings in the Pilomasin basin, Sumatra, by Van Bemmelen;[45] and to the beautiful sliding structures in tuffaceous strata of the Isle of Ischia, Mediterranean, by Rittmann.[46] Endriss[47] made similar observations. Brown[48] has discussed a fine example of an insufficiently consolidated lime-mud, with intraformational layers of limestone pebbles, folded by sliding action. Cartwright[49] also discussed sliding sediments containing pebbles,[50] which are also known from other American deposits. Von Freiberg[51] observed unconformities in a series of the Thuringian Basin with scale-like structures which were eroded. Hadding[52] discussed several interesting phenomena rather unlike, however, the slide of Casalborgone. Hahn[53] described, among others, three deformed zones max. thickness 12 meters) between undisturbed series in Ordovician rocks near Trenton Falls. He suggested relation to tectonic movements. Miller[54] referred these to hard-rock faulting.

Among the other cases discussed by Hahn, his Figure 1 (after Reis),[55] from German Muschelkalk, resembles our Figure 4. Miller has discussed more examples. One of these was discovered by Logan[56] (cf. also Hahn). Henderson[57] and Hölder[58] have discussed some struc-

[41] See ftn. 24.

[42] E. B. Bailey, L. W. Collet, and R. M. Field, "Paleozoic Submarine Landslips near Quebec City," *Jour. Geol.*, Vol. XXXVI (1928), pp. 577–614.

[43] E. B. Bailey and J. Weir, "Submarine Faulting in Kimmeridgian Times, East Sutherland," *Trans. Roy. Soc. Edinburgh*, Vol. LVII, II (1932–33), pp. 429–68.

[44] K. A. F. R. Musper, "Die fischführende Breccien- und Mergelschieferabteilung des Tertiärs der Padanger Hochlande (Mittel-Sumatra)," *Verhand. Geol. Mijnbouwk. Gen. v. Ned. e. Koloniën, Geol. Ser.*, Vol. XI (1935), pp. 145–88.

[45] R. W. van Bemmelen, "Het Boekit Mapas-Pematang Semoet vulkanisme (S. Sumatra)," *Verhand. Geol. Mijnbouwk. Gen. v. Ned. e. Koloniën Geol. Ser.*, Vol. IX (1931), pp. 57–76.

[46] A. Rittmann, "Geologie der Insel Ischia," *Zeitschr. f. Vulkan.*, Add. Vol. VI (1930).

[47] K. Endriss, "Geologie des Randecker Maars und des Schopflocher Riedes," *Zeitschr. d. D. Geol. Ges.*, Vol. XLI (1889), pp. 83–126.

[48] T. C. Brown, "Notes on the Origin of Certain Paleozoic Sediments, Illustrated by the Cambrian and Ordovician Rocks of Center County, Pennsylvania," *Jour. Geol.*, Vol. XXI (1913), pp. 232–50.

[49] L. D. Cartwright, "Sedimentation in the Pico Formation in the Ventura Quadrangle, California," *Bull. Amer. Ass. Pet. Geol.*, Vol. XII (1928), pp. 235–69.

[50] Twenhofel, p. 744 of ftn. 17.

[51] B. von Freiberg, "Der Aufbau des unteren Wellenkalkes im Thüringer Becken," *Neues Jahrb. f. Min., etc.*, Add. Vol. XLV (1921), pp. 214–74.

[52] See ftn. 9.

[53] See ftn. 37.

[54] W. J. Miller, "Slightly Folded between Nonfolded Strata at Trenton Falls, NewYork," *Jour. Geol.*, Vol. XVI (1908), pp. 428–33.

[55] O. M. Reis, "Beobachtungen über Schichtenfolge und Gesteinsausbildungen in der fränkischen Unteren Trias," *Geognost. Jahresh.*, Vol. XXII, Part I (1910) (*non vidi*).

[56] W. E. Logan, *Geology of Canada* (1863) (*non vidi*).

[57] See p. 506, Fig. 19, of ftn. 15.

[58] H. Hölder, "Geologische Untersuchungen in der Umbebung von Lauchheim (Ostalb)," *Neues Jahrb. f. Min., etc.*, Add. Vol. LXXXVI (1942), pp. 315–89 (cf. esp., pp. 341–43, Pl. 25).

tures which, in general, are not comparable. Hölder also considered an occurrence reported by Krumbeck,[59] who has observed strong foldings of various kinds. Kindle[60] has discussed slidings in the tidal zone, which he explained by differential weight of more consolidated and heavier material on soft sediments.[61] Klingner[62] presented a beautiful example of rolling (sliding) sediments, a variant of the snowball structures mentioned by Hadding. Knauer[63] considered finely folded sediments between regularly stratified beds; Kraus[64] structures in Flysch strata of Oberammergau, Bavaria, his Figure 1 resembling our Figure 4.

Krejci-Graf and Liebus[65] briefly mentioned flow structures and sliding folds in Rumanian Upper Eocene strata; Lukovic,[66] Samatrian disturbed and folded strata (according to a review). Simon[67] discussed subaqueous sliding folds in the Upper Cambrian strata near Seville, Spain; De Terra,[68] peculiar structures previously discussed by Knight.[69] Leuchs[70] has described, among others, an interesting small-scale structure. Steuer[71] discussed slidings in Oligocene deposits of Rheinhessen, Germany; and Winkler[72] described Upper Sarmatian structures referred to submarine sliding of fresh lime-mud material, afterward superposed by coarse deposits resting on a sharp plane of erosion. For Knight and Rothpletz,[73] see Twenhofel.[74] Other papers are cited below.[75] Lippert[76] has pub-

[59] L. Krumbeck, "Faltung, untermeerische Gleitfaltung und Gleitstauchung am Tithon der Altmühlalb," *Neues Jahrb. f. Min., etc.*, Add. Vol. LX (1928), pp. 113–64.

[60] See ftn. 13.

[61] Cf. also W. Häntzschel, "Die Schichtungsformen rezenter Flachmeer-Ablagerungen im Jade-Gebiet," *Senckenbergiana*, Vol. XVIII (1936), pp. 316–56 (cf. p. 352); *idem*, "Senkrecht gestellte Schichtung in Watt-Ablagerungen," *ibid.*, Vol. XX (1938), pp. 43–48.

[62] F. E. Klingner, "Sediment-Rollen (Unterwasser-Gleitung) im Muschelsandstein bei Saarlauetern," *Senckenbergiana*, Vol. XXI (1939), pp. 311–13.

[63] J. Knauer, "Überzählige Schichtablagerung und Scheintektonik," *Abhandl. Geol. Landesunters. d. Bayr. Oberbergamt*, Vol. XVII (1935), pp. 47–55.

[64] E. Kraus, "Über Sandsteinwülste," *Zeitschr. d. D. Geol. Ges.*, Vol. LXXXVII (1935), pp. 354–60.

[65] K. Krejci-Graf and A. Liebus, "Tertiäre Foraminiferen aus den rumänischen Ölgebieten," *Neues Jahrb. f. Min., etc.*, Add. Vol. LXXIV (1935), pp. 118–56.

[66] M. T. Lukovic, "Fossil Landslides on the Right Bank of the Danube near Beograd" (Engl. summary), *Vesnik Geol. Inst.*, Vol. VI (1938), pp. 261–65 (*non vidi*).

[67] W. Simon, "Lithogenesis kambrischer Kalke der Sierra Morena (Spanien)," *Senckenbergiana*, Vol. XXI (1939), pp. 297–311.

[68] H. de Terra, "Structural Features of Gliding Strata," *Amer. Jour. Sci.*, (5), Vol. XXI (1931), pp. 204–13.

[69] S. H. Knight, "The Fountain and Caspar Formations in the Laramie Basin," *Univ. Wyoming Publ., Geol.*, Vol. I (1929), pp. 74–78 (*non vidi*).

[70] K. Leuchs, "Feinschichten, Gleitfaltung, Algenrasen und Trümmerlagen im Wettersteinkalk," *Chemie d. Erde*, Vol. VII (1932), pp. 95–112 (cf. p. 97, Fig. 3).

[71] A. Steuer, "Über Rutschungen im Cyrenenmergel bei Mülschim und anderen Orten in Rheinhessen," *Notizbl. d. Ver. f. Erdk. u. Geol. Landesanst. Darmstadt*, Vol. IV, No. XXXI (1910), pp. 106–14 (*non vidi*).

[72] A. Winkler, "Über die sarmatischen und pontischen Ablagerungen im Südostteil des Steirischen Beckens," *Jahrb. Geol. Bundesanst, Wien*, Vol. LXXVII (1927), pp. 393–456.

[73] A. Rothpletz, "Meine Beobachtungen über den Sparagmit und Birikalk am Mjösen in Norwegen," *Sitzungsber. K. Bayr. Ak. d. Wiss. München, math. naturwiss. Kl.*, Vol. XV (1910), pp. 3–66.

[74] See pp. 743–44 of ftn. 17.

[75] A. Briart, "Notes sur les mouvements parallèles des roches stratifiées," *Ann. Soc. Géol. Belgique*, Vol. XVII (1890), pp. 129–35; E. R. Cumings and R. R. Schrock, "The Geology of the Silurian Rocks of Northern Indiana," *Direct. Geol. Dept. Conserv. Indiana*, Publ. No. 75 (1928) (*non vidi*);

[Note 75 continued on next page]

[76] See ftn. 11.

lished an important paper on disturbances of strata, also containing a useful classification of the different phenomena mentioned above. Interesting cases of subaqueous movement were treated in this paper.

FURTHER EXAMPLES OF DISTURBANCE OF STRATA IN THE TURIN TERTIARY

Nontectonically disturbed sediments are exposed at several places in the Turin Hills. In 1941 we discussed clay balls.[77] Other structures call for special attention to a paper by Häntzschel,[78] of which we were not aware in 1941. Häntzschel has discovered chaotic stratification caused by tidal gully action in recent North Sea shoal regions: sliding of small packets of slightly consolidated strata (see below). Other proofs of gully action, discovered in a Helvetian shoal region near the dome of Serra (mentioned above), were described in 1941 and compared with Häntzschel's descriptions of recent North Sea examples.[79] One of the features was a cross-section of a tidal gully, showing Alpine pebbles, which had been shifted back and forth in the tidal zone. Afterward, the gully and its surroundings were eroded and covered by other sediments.[80]

The dome of Serra was one of the shallowest portions of the Helvetian Basin. Besides the gully, we observed further proofs of the existence of a shoal region, which may be compared with the southern North Sea coasts. At many places west of the dome of Serra, but only so far as coarse deposits are known in the Lower Helvetian, we observed a disturbed stratification which reminds us strikingly of the structures figured by Häntzschel, viz., chaotic arrangement of fragments of stratified sediments. We especially saw sections resembling Häntzschel's Figure 3 in all respects. Häntzschel explained this disturbed stratification as follows: Washing of strata in the steep sides of gullies, which are well known in the tidal zone of the North Sea shoal regions, is involved in the gradual shifting of the course of the gullies. Through this operation of small gradual movements, sediment packets, which are more or less consolidated, glide down and ac-

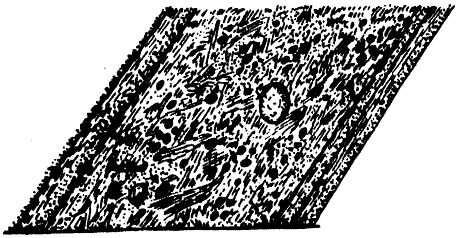

FIG. 7.—Middle Tongrian near Casa Nicolletti in the eastern Turin Hills, containing Alpine pebbles and showing "gully structures." Scale about 1:80.

P. E. Kent, "Contemporaneous Disturbances in Lacustrine Beds in Kenya," *Geol. Mag.*, Vol. LXXXII (1945), pp. 130–35; P. G. Kraus, "Weitere Beobachtungen im Tertiär und Diluvium des Niederrheins," *Jahrb. Preuss. Geol. Landesanst.*, Vol. XXXVIII, Part I (1919), pp. 183–200; F. Lotze, "Zur Erklärung der Querplattung (Sigmoidalklüftung) im Wellenkalk," *Centralbl. f. Min., etc., B* (1932), pp. 300–307; H. Nathan, "Geologische Untersuchungen im Ries," *Neues Jahrb. f. Min., etc.*, Add. Vol. LIII (1925), pp. 31–97; N. B. Vassoevich, "On the Problem of the Large Submarine Landslips (Eng. summary)," *Trans. Oil Inst. Moskau Leningrad* (1935) (*non vidi*); R. Weyl, "Stratigraphie und Tektonik der Grundgebirgsgrenze zwischen Kinzig und Elz im mittleren Schwarzwald," *Badische Geol. Abh.*, Vol. VIII, Part I–II (1936), pp. 46–126 (*non vidi*).

[77] See Beets, *De geologie van het westelijk . . . .*, p. 33 (Pl. I, Fig. 1), 49, 90–91 (Figs. 4, 5); and Beets, "Die Geologie . . . . ," pp. 206 (Fig. 3), 207, 214, 238–40 (Figs. 10–11), of ftn. 2.

[78] See ftn. 61 (1938).

[79] See ftn. 61 (1936).

[80] See Beets, *De geologie . . . .*, pp. 92–93, Fig. 6; and Beets, "Die Geologie . . . . ," p. 240, Fig. 12, of ftn. 2.

cumulate in disorder in the bed which is being left by the shifting gully. This explanation will apply to the Helvetian structures near the dome of Serra as well.

As stated in 1941,[81] chaotic sediment packets are also known from part of the Middle Tongrian in the eastern Turin Hills. We here repeat as Figure 7 the sketch published in 1941, which shows jumbled marl packets, clay balls of local derivation,[82] and pebbles of Alpine origin.

The geologic data point to a near-by coastal line, along which Alpine pebbles were transported from west to east and deposited mainly south of Casa Nicoletti (this spot lies north of the main transport zone, which started in the delta zone along the Pennine Alps and followed the south coast of an anticlinal structure in the Turin basin, ending in the vicinity of Casa Nicoletti).[83] Now and then Alpine pebbles and clay balls were transported to the marly region of Casa Nicoletti, where they were mixed with locally formed marl packets. In 1941 we tried to explain the marl packets by washing by "sea-currents"; but now we prefer to explain them, including the whole sedimentation near Casa Nicoletti, by a special kind of current operation, viz., by gully action in a broad tidal zone along the eastern extremity of the anticlinal structure which formed a land-strip during Oligocene time. The Alpine pebbles were transported from the southern accumulation of coarse deposits by gully action, which, moreover, at Casa Nicoletti caused chaotic stratification of marly sediments. The clay balls were derived from deposits in the vicinity of their present locality.

[81] See Beets, *De geologie* . . . . , p. 90, Fig. 4; Beets, "Die Geologie . . . . ," p. 238, Fig. 10, of ftn. 2.

[82] Cf. Häntzschel's Fig. 1 of ftn. 61 (1938).

[83] See Beets, *De geologie* . . . . , p. 80, Map I, and "Die Geologie . . . . ," p. 230, Map I, of ftn. 2.

ORIGIN OF THE LACKAWANNA BASIN, PENNSYLVANIA[1]

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ABSTRACT

The Lackawanna Basin or Northern Anthracite Field lies in northeastern Pennsylvania between the Allegheny Plateau on the west and the Pocono Plateau on the east. Structurally, it resembles similar long, narrow synclines of the Appalachians, but its trend is different. Data on thicknesses of formations indicate a marked thinning of the Mississippian under the basin. Its presence is attributed to this thinning, because during the Appalachian Revolution here was a region of structural weakness.

LOCATION

If one examines a geologic map of Pennsylvania, he will see in the northeastern quarter of the state the Anthracite Fields, producing area of most of our "hard coal." A region of folded strata, the structural trend and the physiographic expression of the fields conform with those of the Appalachian Mountains, of which they form a part. However, like the proverbial rule, this last statement has its exception. Springing from the northeastern corner of the main body of the Anthracite Fields, and extending northeastward for some 70 miles nearly to the New York State line, is a long, narrow syncline called the Northern Anthracite Field or the Lackawanna Basin. Wedged between the Allegheny Plateau on the west and the Pocono Plateau on the east, this anomalous structure has the characteristics of the larger, fusiform Appalachian synclinal basins; but its northeast by southwest alignment fails to conform with the more nearly east-west trend of the mountains of northeastern Pennsylvania. To appreciate more fully this anomaly, note the general physiographic aspect of the northwestern three-fourths of the state.

PHYSIOGRAPHIC SETTING

The Allegheny Plateau embraces most of the western half of Pennsylvania and extends into the northeastern quarter of the state. It is separated on the east and south from the ridges and valleys of the Appalachian Mountains by an escarpment, the Allegheny Front. From the state's south-central border, the "Front" sweeps in a long arc northeastward, forms the northern boundary of the principal Anthracite Fields, and eventually passes eastward into New York by way of the Delaware River Valley. The Allegheny Plateau breaks off abruptly at the Lackawanna Basin. This long, narrow, coal-measure-filled syncline separates the larger plateau from the lesser Pocono Plateau to the east. The Pocono Plateau resembles physiographically and geologically the Allegheny Plateau but is of much smaller extent, confined between the Anthracite Fields and a great bend in the Delaware River. Yet, despite their similarity, it is doubtful if these plateaus were ever continuous across the region of the Lackawanna Basin.

STRUCTURES AND STRATA

The rocks which crop out on the Allegheny Plateau belong to the Devonian, Mississippian, Pennsylvanian, and Permian systems. The Pocono

[1] Published with the permission of the State Geologist of Pennsylvania.

Plateau is capped chiefly by Devonian strata with a little Mississippian along its northern and western margins.[2] In general, the bedding is nearly horizontal, but the uniform structure of the Allegheny Plateau is interrupted by shallow synclines and gentle anticlines which are similar in trend to the Appalachian Mountain structures of much greater plunging synclines of the neighboring Anthracite Fields, and along the northern border adjacent to the Lackawanna Basin, where they dip abruptly under that structure (see Fig. 2).

The Lackawanna Basin as stated is an isolated bit of intense Appalachian type of folding. It is a structural anomaly in that it was developed between the two

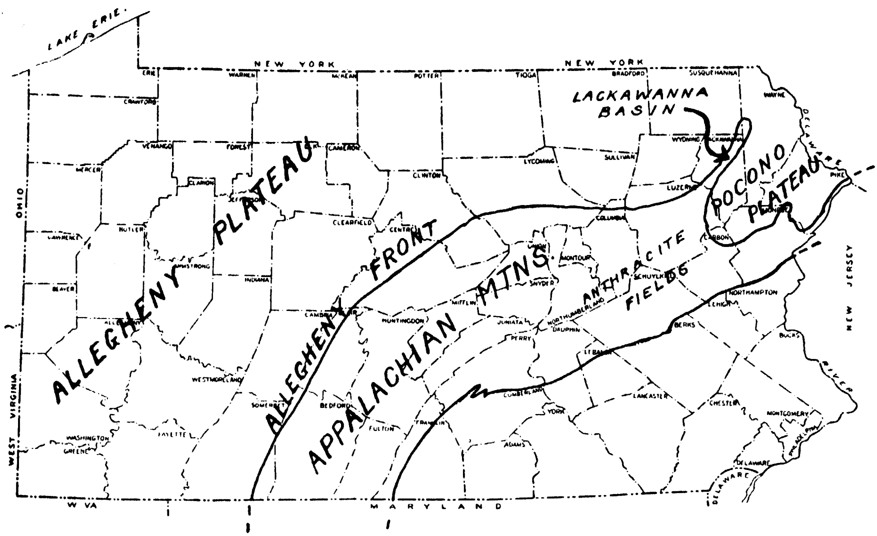

FIG. 1.—Outline map of Pennsylvania showing the location of the Lackawanna Basin and its relations to the major physiographic features of the state.

amplitude to the east. This relation is significant because it helps to set off structurally the plateau synclines from the Lackawanna Basin. The formations of the Pocono Plateau dip very gently and uniformly northwestward except along the western border of the upland, where the beds are thrown into crenulations across the ends of the westward- plateaus, and its intensity is quite unlike the shallow synclines of the Allegheny Plateau, nor is it aligned with the neighboring Appalachian structural trends. To understand these peculiarities, it is necessary to summarize the local Devonian and Mississippian stratigraphy.

The Devonian of the Pocono Plateau, as of most of northeastern Pennsylvania, is essentially confined to the thick Catskill continental facies.[3] The succession is:

[2] Anomalously, the Pocono Plateau was for years assumed to be the type locality of the Pocono formation due to a long-standing confusion of that unit with the Honesdale sandstone of the Devonian. Cf. Bradford Willard, *Pa. Topog. and Geol. Surv. Bull. G19* (1939), p. 304.

[3] *Ibid.*, chap. viii: "The Devonian of Pennsylvania."

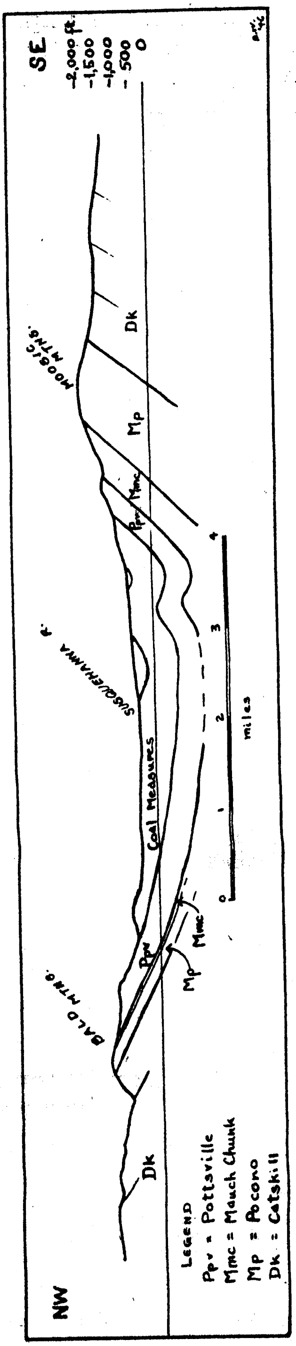

FIG. 2.—Somewhat generalized northwest by southeast section across the Lackawanna Basin in the vicinity of Wilkes-Barre

Mount Pleasant red shale
Elk Mountain sandstone
Cherry Ridge red shale
Honesdale sandstone
Damascus red shale
Shohola sandstone and shale

This whole succession of alternating red and nonred units closely resembles in lithology the overlying Mississippian. Despite heavy glaciation across the Plateau, outcrops indicate that over most of the upland the Catskill is distributed in a succession of broad northeast- to southwest-trending bands roughly parallel to the Lackawanna Basin. Successively older units crop out toward the southeast. The Catskill dips beneath the Lackawanna Basin and emerges on its northern flank, whence, westward, most of it passes gradually into the marine Devonian formations of north-central Pennsylvania. Throughout there is a gradual, uniform thinning from the Plateau westward (cf. Fig. 2).

The Mississippian formations of the Plateau are a simplified repetition or continuation of Catskill lithology. The system consists of two major units: Mauch Chunk red shale and Pocono sandstone and conglomerate.

The Mississippian in northeastern Pennsylvania is well exposed along the northern and western borders of the Pocono Plateau. It supports the Moosic Mountains, which separate the plateau from the basin, and it occupies the troughs of westward-plunging synclines in the Anthracite Fields west of the plateau. The Mississippian beds, like the Catskill, dive under the Lackawanna Basin. Similarly, they emerge along its farther side. Here, however, the analogy with the Devonian lessens. The Mauch Chunk, instead of passing into a marine facies, pinches out completely with no hint of salt-water conditions and but little litho-

logic change. The Pocono formation also thins but does not completely vanish. After the manner of the Devonian, its attenuated remnant merges with the marine Mississippian of north-central Pennsylvania.[4]

The decrease in thickness of the Mississippian system takes place chiefly in an astonishingly short distance beneath the Lackawanna Basin (Figs. 2 and 3). In the Moosic Mountains opposite the middle and southern parts of the basin, it attains a thickness of some 3,000 feet. Along the western border opposite, the system reappears with a thickness of only 300–500 feet. This remarkable change has taken place in a linear distance of only 6 or 8 miles.

That the Mississippian once spread across the Pocono Plateau is inferred from its abrupt eastern termination in the face of the Moosic Mountains and from its thickness under the coal measures to the west of the plateau. Further support of this supposition is had from additional observations and deductions based upon marine-continental relations in Pennsylvania during most of the Paleozoic. This has been discussed in an earlier article.

Throughout the Paleozoic there have been in Pennsylvania recurrences of continental facies tending repeatedly to displace their marine contemporaries. The recurrence may be more or less cyclic. These displacements have been referred to as continental to marine facies shifts. Actually, the freshwater beds themselves display two marked cumulative changes independent of their displacement of the marine beds. First, there is a progressive, chronological evolution from red to non-red rock color. . . . . Second, there is a progressive shift in position or westward and northwestward spreading at each recurrence of continental beds. . . . . Each successive continental facies . . . . spreads farther west or northwest than did its predecessor. In each there is a progressively greater encroachment of freshwater strata upon the Appalachian geosynclinal seaway.[5]

In addition to the above, the maximum thickness of the several continental facies of the systems migrated westward or northwestward. In the Silurian, maximum continental deposition appears to have occurred in northern New Jersey. In Devonian times the thickest Catskill was laid down in the region of the Upper

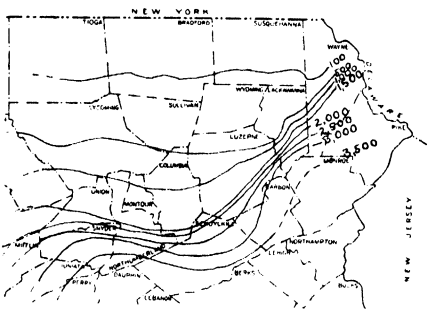

FIG. 3.—Isopach map of the Mississippian system in northern Pennsylvania, based principally upon field work by the author.

Delaware Valley. The maximum of Mississippian fresh-water beds probably occupied the present region of the Pocono Plateau. Finally, the thickest Pennsylvanian deposition took place in the Anthracite Fields. Such a shift may be attributed to progressive uplift of the general region to the east and southeast from which sediments were derived, causing erosion and partial re-working of the more remote, older beds whose debris was incorporated into newer formations to the west and northwest. This movement might be termed a

[4] For a full account of this change see Bradford Willard, "Continental-Marine Mississippian Relations in Northern Pennsylvania," *Bull. Geol. Soc. Amer.* (in press), and abstract in "Proceedings" of 1945 meeting.

[5] Bradford Willard, "Recurrent Paleozoic Continental Facies in Pennsylvania," *New York Acad. Sci., Annals*, Vol. XL, Art. 4 (1940), p. 284.

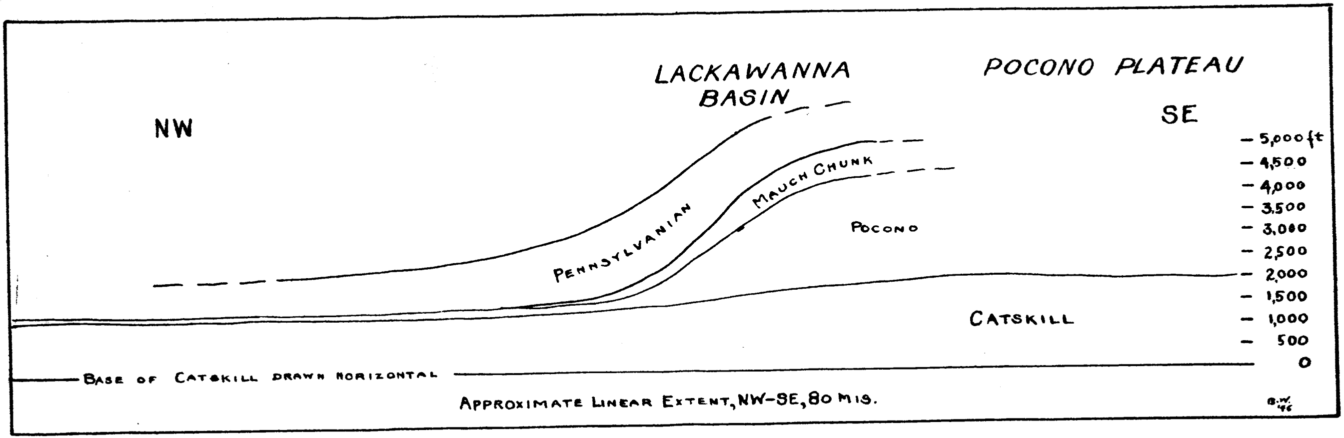

FIG. 4.—Restoration of northwest by southeast section through the regions of the Lackwanna Basin and the Pocono Plateau toward the close of Paleozoic time. Note the horizontal position of the basal Catskill. Presumably, from its present position, comparatively little isostatic adjustment affected the continental formations here involved.

migration of the geanticline rather than a migration of the geosyncline. If so, the Mississippian probably reached its maximum thickness in the region of the plateau, east of which its distribution was quite limited.

HISTORY

If we reconstruct late Paleozoic conditions in northeastern Pennsylvania, we find that the continental Devonian is overlain by continental Mississippian and this in turn by the fresh-water-formed Pennsylvanian. Presumably, all three systems extended east of their present boundaries, but, as suggested, the maximum Mississippian sedimentation probably occurred in the Pocono Plateau region. The reconstructed section is shown in Figure 4. Note the regular, progressive thinning of the Devonian and the abrupt change in thickness of the Mississippian. This abrupt change coincided with the region today marked by the synclinal Lackawanna Basin. Such a change in thickness might be a potential line of structural weakness.

When the Appalachian Revolution set in, the Paleozoic formations of northeastern Pennsylvania were pushed northwestward. Formations well to the east, presumably terminating in the thinning Devonian, crumpled; but in the region of the Pocono Plateau, the heavy, thick Catskill and even thicker Mississippian and perhaps some coal measures formed a competent bastion. Instead of folding, it transmitted the thrust. But, at the line of thinning of the Mississippian, downbuckling took place to form the Lackawanna Basin. Subsequent uplift and erosion cleared the Pocono Plateau of all but remnants of the Mississippian and exposed the Devonian beds, but the downwarping preserved the Mississippian and Pennsylvanian of the basin.

ORIGIN OF CERTAIN WIND GAPS IN THE LARAMIE MOUNTAINS, WYOMING

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ABSTRACT

Wind gaps in the Laramie Mountains, Wyoming, are described. The wind gaps are due to superposition of streams upon the pre-Oligocene topography and later capture by headward eroding tributaries. The tributaries are able to extend their valleys headward more rapidly than the main stream because of the soft Tertiary sediments in which they head.

INTRODUCTION

The Laramie Mountains of Wyoming are the northern structural and topographic continuation of the Front Ranges of Colorado and are included by N. M. Fenneman[1] in the Southern Rocky Mountain Province. The principal geologic features of the range, and the wind gaps described, may be located on the index map (Fig. 1). The range in broad outline is an asymmetric anticline, with a steep eastern limb and a gently dipping western limb. The basic pattern is modified by thrusting and transverse faulting and local folds of reverse asymmetry, as well as folds which trend transverse to the principal northwest-southeast axis of the uplift. The sedimentary sequence ranges from Mississippian (?) to late Tertiary and is adequately described by N. H. Darton,[2] hence is not presented here in detail. The physiographic features of the Laramie Mountains were first described by Eliot Blackwelder[3] and have been further discussed by T. S. Lovering,[4] F. M. Van Tuyl and Lovering,[5] J. L. Rich,[6] and C. J. Hares.[7]

The Laramie Range came into existence during the Laramide revolution. The Cretaceous Lance and Paleocene Fort Union formations were deformed and later unconformably overlain by the Eocene Wasatch in the Powder River Basin, northeast of the Laramie Mountains. The Wasatch formation was later deformed and the mountains eroded deeply, so that a drainage pattern developed, moderately well adjusted to rock structure. It is possible that a part of this erosion took place in the late Eocene and continued into the early Oligocene. Resistant rock units were expressed as hogbacks or as topographic prominences.

Oligocene and Miocene sediments were deposited by aggrading streams in the pre-Oligocene valleys. The older topog-

[1] *Physiography of Western United States* (New York: McGraw-Hill Book Co., 1931).

[2] Laramie-Sherman Folio, *Geologic Atlas of the United States*, No. 173 (1910).

[3] "Cenozoic History of the Laramie Region, Wyoming," *Jour. Geol.*, Vol. XVII (1909), pp. 429–44.

[4] "Geologic History of the Front Range, Colorado," *Proc. Colo. Sci. Soc.*, Vol. XII, No. 4 (1929), pp. 59–111.

[5] "Physiographic Development of the Front Range," *Bull. Geol. Soc. Amer.*, Vol. XLVI (1935), pp. 1291–1350.

[6] Discussion of Lovering and Van Tuyl papers, *Bull. Geol. Soc. Amer.*, Vol. XLVI (1935), pp. 2046–51.

[7] "Deeply Weathered Pre-Cambrian Peneplain a Basic Factor in the Genesis of the Sherman Flat Surface, Laramie Mts., Wyoming," *Proc. Geol. Soc. Amer.* (1934), p. 81. (Abstract.)

raphy on the margin of the mountains was buried, and in places Tertiary sediments extended across the crystalline core of the range (see Fig. 1). The maximum height of the Tertiary flood-plain surface is not known. It was high enough, however, to allow extensive overlap of Tertiary materials onto the pre-Cambrian crystalline core of the mountain mass. The Tertiary section of this area includes the White River group, composed of the Chadron and Brule formations and the Miocene Arikaree group, as defined by A. L. Lugn[8] in western Nebraska.

The region was excavated in post-Miocene time, and much of the Tertiary

[8] "Classification of the Tertiary System in Nebraska," *Bull. Geol. Soc. Amer.*, Vol. L (1939), pp. 1245–76.

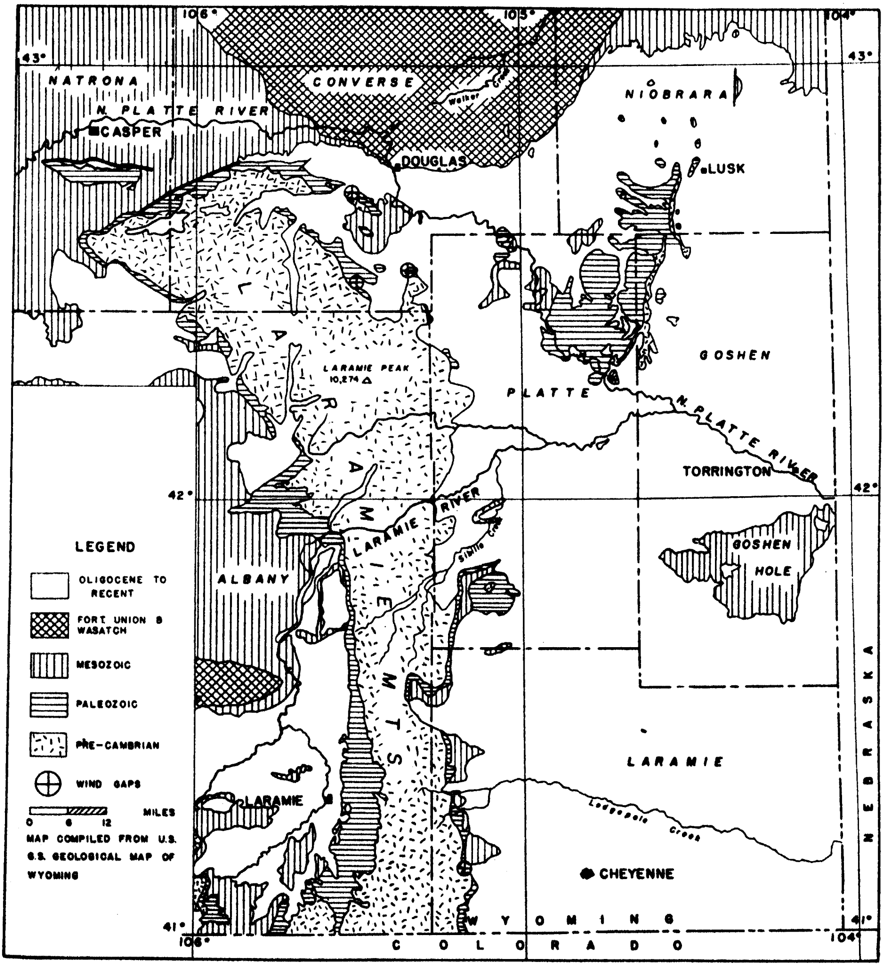

FIG. 1.—Index map of a portion of Wyoming, indicating the regional geology and the location of observed wind gaps.

sediment has been removed. In this excavation the drainage pattern of streams that previously flowed on the depositional surface of the Tertiary sediments has been in part superposed on older strata. The major streams were superposed over major structural features, as illustrated by the course of the North Platte River across the Hartville uplift in eastern Wyoming. Minor streams show equal disregard for structure in many cases. Wind gaps and meander scars developed and are in the process of development in the readjustment of drainage that is still taking place. Some consequent streams developed, as the Tertiary cover was removed, and are adjusted to underlying structure on both sedimentary and pre-Cambrian crystalline rocks. The wind gaps to be described have been observed on the ground and on aerial photographs prepared for the United States Forest Service. These wind gaps are due to a type of stream piracy in which a tributary pirates the main stream. R. S. Sharp[9] has described the wind gaps in northwest Wyoming due to piracy by tributaries but without superposition from unconformable cover. Headward erosion by the tributaries depends upon a favorable differential in rock hardness. A detailed description of the Laramie Mountain wind gaps and their formation follows.

DEERE CREEK WIND GAP

The most conspicuous wind gap seen by the writer is located on Deere Creek, in Sec. 7, T. 29 N., R. 72 W., Converse County, Wyoming. The geologic relationships in this area are shown on Figure 2. Deere Creek and its tributaries head either on the pre-Cambrian crystalline rocks or on the unconformable Tertiary cover. The general northeast trend of the stream is influenced by a pronounced N. 35° E. strike in the structure of the pre-Cambrian rocks. Deere Creek is superposed across a sharply folded anticline in T. 30 N., R. 71 W., as it flows from the wind gap to the North Platte River.

At the Deere Creek locality the Pennsylvanian Hartville limestones strike N. 70° W., and dip 12° N.E. to form a southwest-facing escarpment along the flank of the mountains. The present gross topography is a broad, shallow, exhumed valley, cut in both crystalline pre-Cambrian and later sedimentary strata. In this broad valley lie remnants of Tertiary White River sediments. The wind gap lies on the south side of Deere Creek and is incised in a pink granite intruded by basic dikes. The gap, in part, parallels the strike of the dikes and the jointing. The floor of the wind gap has a steep gradient, and at present the east end does not enter the main valley at grade. The walls are essentially vertical owing to the jointing in the granite, and are more than 150 feet high.

While Deere Creek occupied this gap, the rate of downcutting in the section of the channel upstream from the gap was retarded, because of the establishment of a local baselevel upstream from the barrier of crystalline pre-Cambrian rocks. Immediately downstream from the gap, downcutting was accelerated because of the relatively softer sediments over which the stream flowed in the filled pre-Tertiary valley.

The accelerated erosion in the stream course downstream from the gap likewise accelerated the downcutting in the tributaries that entered Deere Creek below the gap. One of these tributaries eroded headward in the Tertiary fill in a

[9] "Superposed Windgaps of Cedar Mountain, Wyoming," *Jour. Geomorph.*, Vol. IV (1941), pp. 325–27.

position parallel to the gap and also approximately parallel to the axis of the pre-Tertiary valley. The tributary, advantageously situated on the Tertiary fill, was able to erode a channel to a lower elevation than the portion of Deere Creek above the gap. The tributary eroded headward until it captured the master-stream, causing it to abandon the incised gorge in the granite that is now the Deere Creek wind gap.

The new channel of Deere Creek, located on the Tertiary fill, was rapidly deepened until granite was again exposed. The stream incised a second gorge in the granite and has continued to occupy it because the excavation of the pre-Oligocene valley is essentially complete at this point. No tributary is able to cut rapidly headward at the expense of the master-stream and effect a capture unless there is a marked differential in resistance to erosion due to softer strata in part of the course.

The establishment of the channel of the stream at the Deere Creek wind gap may have taken place in one of two ways. First, the stream may be considered to have been superposed on the granite, as described above. This interpretation depends on the height on the mountain flanks to which the Tertiary fill reached before excavation began.

A second possibility is that the position of the gap is approximately at the point of a previous contact between the granite and the Tertiary fill. In this case Deere Creek may have been flowing in a

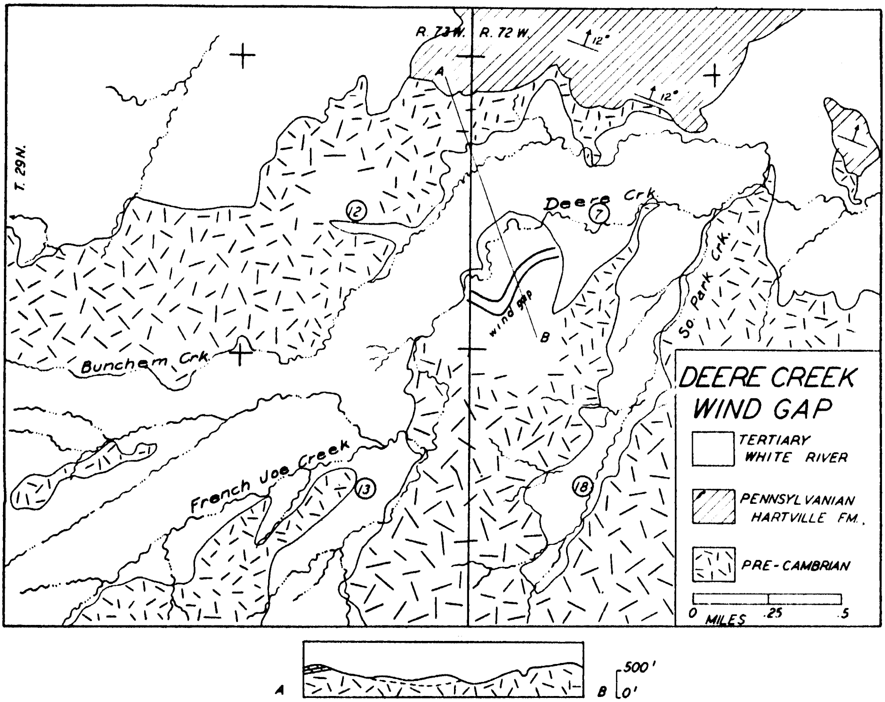

FIG. 2.—Geologic map and cross section of the Deere Creek wind gap

structurally controlled channel to a point at the lower end of the gap, where it debouched upon the Tertiary fill. The capture that caused the wind gap took place, then, by a tributary flowing on the fill under more favorable conditions for channel deepening.

The evidence from localities described below lends support to the first interpretation.

TRAIL CREEK

Excellent examples of small-scale wind gaps or meander scars were observed near the headwaters of a tributary to Trail Creek, in Sec. 26, T. 30 N., R. 71 W., Converse County, Wyoming (Fig. 3). At this locality the Pennsylvanian Hartville formation is exposed in a northwest-plunging fold. The axis of the fold trends N. 20° W., and the strata on the west flank strike N. 40° E. and dip 23° N.W. This fold extends northward from the mountains and is unconformably overlapped by the fine clays and silts of the Oligocene Brule (?) formation. Pre-Cambrian crystalline rocks are exposed 2 miles south of the map area in normal stratigraphic position. The pre-Brule topography was a rather broad, north-trending valley, excavated in some of the softer strata of the Hartville formation. Trail Creek established a northward-flowing position toward the master-drainage of the North Platte River and, together with its tributaries, began to excavate the immediate area. The tributary of Trail Creek under consideration (in Sec. 26) eroded down to the hard dolomitic limestones of the Hartville formation. When this formation was exposed, the small intermittent stream (at least, so it is now) incised portions of three meanders into the more resistant Hartville formation.

The Tertiary strata west of the incised meanders are thicker because of the relationship of the westward-dipping contact between the Hartville formation and the Tertiary. The tributaries eroded headward, in courses parallel to, and west of, the main stream. The tributaries thus lowered their channels (see cross section, Fig. 3) and captured the main stream in such a manner as to isolate the meanders, which were incised in the Hartville formation. The abandoned portions of the stream course remain as small-scale wind gaps or meander scars.

The largest of these wind gaps (*a* in Fig. 3) is $\frac{1}{8}$ mile long, about 40 feet deep, and 25–30 feet wide at the floor. This gap is now about 50 feet above the present stream channel. Two shorter wind gaps (*b* and *c* in Fig. 3) occur to the south (upstream), at elevations which suggest that they represent portions of one continuous channel at a particular stage in the downcutting. The gradient obtained by connecting the floors of channels *a* and *b* is moderately steep but was not determined by instrument.

The channel marked *c* (Fig. 3) and now occupied by the stream has the same characteristics as the meander scars at *a*, *b*, and *d*. The stream occupies a channel 15 feet deep, 200 feet long, and about 10 feet wide, incised in limestone. Immediately upstream and downstream from the incised channel, the stream is at present eroding a channel in soft Tertiary fill. A minor intermittent tributary is eroding headward in such a fashion that a very narrow, low divide exists between the major and the minor streams. Capture is imminent. When capture takes place, *c* will be isolated as a meander scar similar to those mentioned above.

The method by which the capture took place is well illustrated at the Trail Creek locality. A repetition of capture occurred, so that a second meander scar

developed on the same exhumed slope, but at a lower elevation. Apparently, the stream in a part of its course incised a new channel (*d*) in the limestones and dolomites, while the upper reaches continued to occupy the previously cut notch (*c*). The two sets of wind gaps thus give a measure of the effect on down- bedding planes of the resistant strata, with a resulting overhang of the cliff on the down-dip (north) side of the gorge. The stream flows over Tertiary strata both upstream and downstream from the canyon. Sand and gravel derived from conglomerate lenses in the Tertiary sediments upstream serve as tools by which

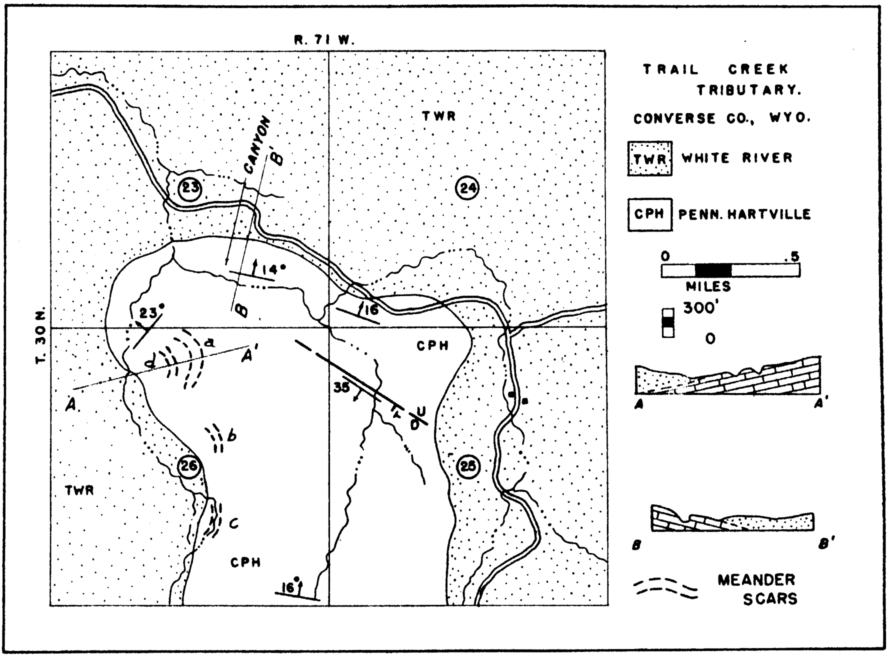

FIG. 3.—Geologic map and cross section of the Trail Creek tributary area, with location of wind gaps

cutting caused by the disturbance of local baselevel.

Superposition of a stream upon the Hartville group of rocks in the S.E. $\frac{1}{4}$ of Section 23 (Fig. 3) has set up the conditions necessary for a potential capture in the same vicinity. A canyon has been eroded into limestones and dolomites that dip 14° northeast. The gorge is 40–60 feet wide at the floor and over 100 feet in depth. The stream has shown some tendency to migrate down dip along the the stream rapidly erodes the limestones and dolomites.

A tributary heading eastward from the center of Section 23 is separated from the main stream by a low divide near the boundary line between Sections 23 and 24. In this case it is possible that the major stream, because of the clastic materials available to it and its greater volume of water, may be able to lower the main channel in hard rocks faster than the tributary, eroding headward in soft

material, can shift the divide. The conditions are potentially suitable for capture, and abandonment of the major channel will form a wind gap.

BED TICK CREEK

This locality is in Secs. 31 and 32, T. 32 N., R. 72 W., Converse County, Wyoming, at the headwaters of Bed Tick Creek (Fig. 4). One of the thickest sections of White River strata in the region is here exposed along the north side of the valley. The present drainage is roughly parallel to the north flank of the exhumed La Bonte anticline. The elevation of the exposed crystalline core of this anticline is 1,400 feet higher than the surrounding country. The Tertiary White River sediments overlap steeply dipping hogbacks of Paleozoic and Mesozoic rocks on both the southwest and the northeast limbs of the fold. At the head of Bed Tick Creek the stream gradient steepens rapidly, where the streams are actively cutting headward (west) and creating an erosional scarp upon the White River sediments. The main channel of the stream has been superposed upon the Hartville formation in three places, through which it has cut canyons, approximately 100 feet deep, $\frac{1}{8}$ mile long, and some 50 feet wide at the bottom. The existing canyons have not been isolated to form wind gaps or meander scars, but the condition has almost been attained in two cases.

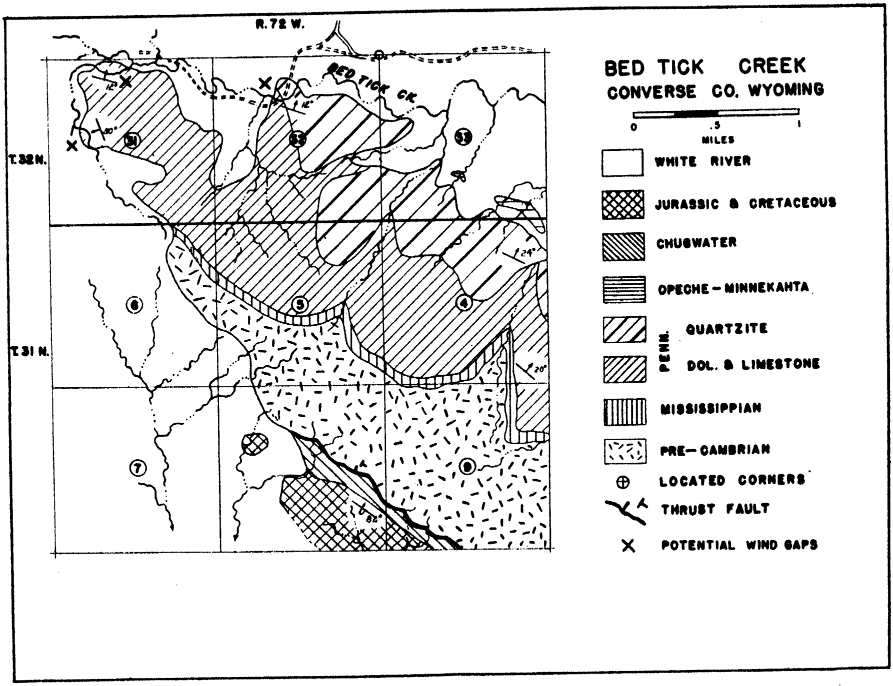

FIG. 4.—Geologic map of the Bed Tick Creek area and location of potential windgaps

The middle canyon (N.E.-N.W. Sec. 31, T. 32 N., R. 72 W.) is most nearly

isolated. On the north rim of the canyon the observer may stand upon soft Brule clay and look directly south into the incised channel cut into the dolomite of the Hartville formation. Immediately to the north, the observer may look into a narrow, steep-sided gully, eroded in the fine-textured clays and silts of the Brule formation. This tributary gully now heads within approximately 300 feet of the main stream, and the elevation of the tributary channel is essentially that of the gorge in the Hartville dolomite. Bed Tick Creek above the gorge swings to the south and southeast in a broad semicircle, and at a distance of approximately ½ mile south it occupies a smaller incised notch.

The tributary drainage heads to the west and is not at present paralleling the master-stream but tends to diverge at an angle. The actual capture will probably be accomplished by a minor tributary.

LARAMIE-SHERMAN FOLIO, WYOMING

An examination of the Laramie-Sherman Folio, *Geologic Atlas of the United States*, No. 173, has revealed another potential wind gap in the process of development. This locality has not been visited in the field but was studied from the topographic and geologic maps and appears to be similar to those already described in detail. The locality is near the corner common to T.'s 13 and 14 N., and R.'s 69 and 70 W., Wyoming. A fork of Crow Creek, unnamed upon the topographic map, flows across this area. The stream heads on the Sherman granite and flows eastward across granite, gneiss, and schist and then across a small area of Oligocene Brule formation, before resuming its course over gneiss and schist finally to reach the plains along the east side of the mountains. The portion of the course between the two Tertiary exposures is in a moderately deep valley cut into the metamorphic rocks.

An intermittent tributary, which enters the Middle Fork of Crow Creek in Sec. 21, T. 14 N., R. 69 W., is eroding headward across Tertiary sediments and, if the fill is deep enough, will eventually capture the unnamed fork of Crow Creek. In this case the capture would be effected not by a tributary of the master-stream itself but by a parallel drainage and would entail a greater readjustment of drainage.

CONCLUSIONS

The described wind gaps are due to drainage changes in a superposed drainage pattern by headward erosion in the unconformable cover. Moderate to strong relief in the topography preceding the deposition of the cover has aided in the process of drainage rearrangement.

The position of the highest wind gaps is a measure of the depth of fill deposited by the late Tertiary streams. A study of the character of the unconformable late Tertiary sediments indicates that much of the material was not locally derived and was laid down as a widespread alluvial deposit.

ACKNOWLEDGMENTS.—The writer wishes to acknowledge the field assistance of John Webb and the support of the Geology Department of the University of Missouri in the purchase of aerial photographs.

BISON-POLISHED BOULDERS ON THE ALBERTAN GREAT PLAINS

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University of Chicago

During a nine-thousand-mile traverse of the drift-covered plains of southern and central Alberta and adjacent Saskatchewan, the writer saw several dozen glacial boulders which carried more or less complete bands of polish on vertical and near-vertical sides, the polish limited to projections—nowhere occurring in the pits, pockets, or indentations of the boulder's surface. None of these boulders was polished on the top or on gentle upper slopes. Limestone boulders carried almost as good a polish as those of quartzite. On granite boulders there was no difference in degree of polish on adjacent quartz and silicate grains.

Boulders less than about five feet in diameter do not possess the polish. Up to perhaps fifteen or twenty feet in diameter, polish-bearing boulders all are surrounded by a moat, an encircling depression in the drift. Still larger boulders have no moat or have a very weakly developed one. No polished surfaces are more than five or six feet above the immediately adjacent ground surface. On those without the surrounding moat the belt is limited to a width of two or three feet—rarely extends down to the ground.

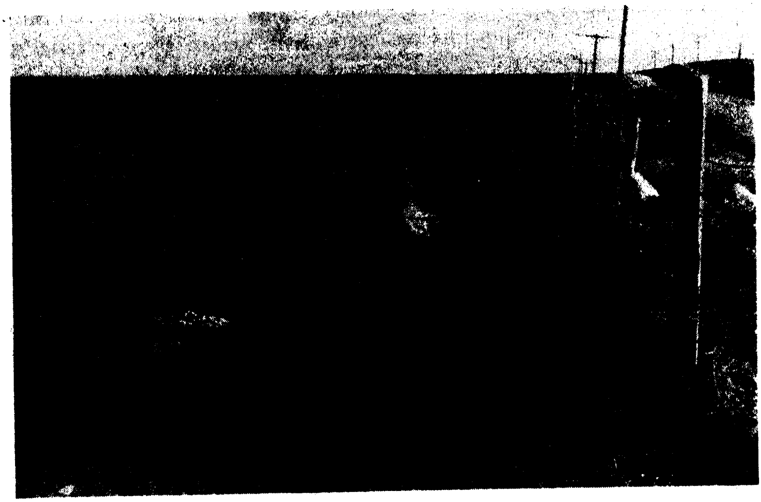

FIG. 1.—Granitic erratic boulder with polished edges, down in a basin whose outer part constitutes a moat which has been shallowed subsequently by wash. South of Macklin, Saskatchewan.

The theory embodied in the title of this paper explains the moat as a result of the trampling of generations of bison, breaking the grass cover while rubbing against the boulder. Wind blew away some of the bare soil, and, when the

FIG. 2.—Limestone erratic boulder, with polished edges. Crawling Valley, north of Bassano, Alberta. Tall grass somewhat obscures the moat. Photo by Paul Herbert.

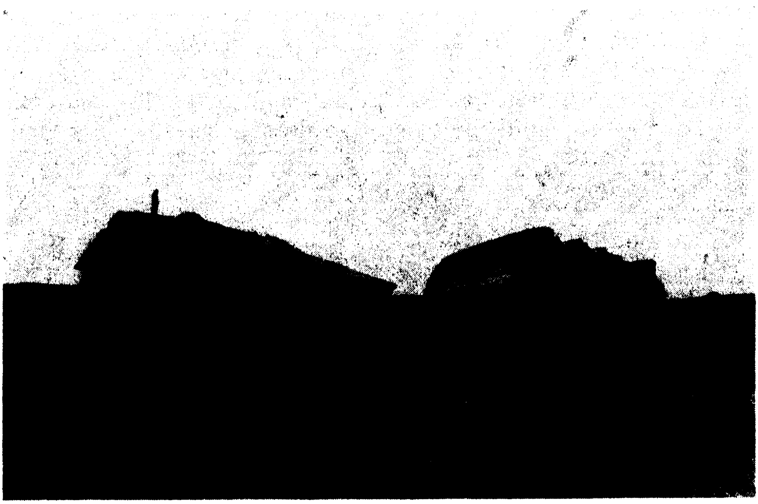

FIG. 3.—Gigantic quartzite erratic boulders near Black Diamond, Alberta. Inconspicuous development of moat. Polish limited to lower 4 or 5 feet of sides of boulders.

ground was wet, bison carried mud away between their cloven hoofs.

The theory must also explain the fact that if these moats were refilled today many boulders would project so little above the drift that no rubbing-place would be provided. An additional item is therefore needed. It is as follows:

Much bentonitic material has been incorporated in the Albertan plains drift from underlying Cretaceous and Eocene shales, and this clay till, when wet, is extremely slippery. A special zigzag steering technique is needed to keep the rear wheels of a car from slipping off the low crown of a recently scraped earthen road surface wet after a brief rain. This same lubrication of wetted till, where an incipient moat has collected water and caused saturation beneath the boulder, has allowed the mud to be slowly squeezed out by the weight of the boulder, later to be tracked away as such or blown away when dry. Thus the moats have been deepened and the boulders have continued to settle until the tops of some are down to the level of the surrounding till surface.

Very large boulders roofed over and protected the underlying till surface from this softening procedure, hence have settled very little, if at all, and possess only a suggestion of the moat.

The character of the polish and the pattern of its distribution is convincing evidence that neither glacial nor wind abrasion is responsible. Mudflow polish on these boulders is nearly as improbable as gastrolith polish. The recency of action is indicated by the freshness of the gloss on the limestone boulders.

Although domestic cattle now use some of these boulders for rubbing-places, it seems impossible that the degree of polish and the depth of moat could have been produced by them in the few decades since the bison disappeared. The road and fence shown in Figure 1 came with settlement of Macklin, Saskatchewan, and with the introduction of cattle. The moat obviously was already there.

REVIEWS

Den sista nordiska nedisningens förlopp ("History of the Last Nordic Glaciation"). By ERIK LJUNGNER. (*Geol. Fören. Förhandl.*, Vol. LXVII.) Stockholm, 1945. Pp. 225–40.

This study is largely based on a chronological separation of the *roches moutonnées*, or glaciated knobs, in Swedish Lapland at about 17° E. and the Polar Circle. Hardness, location, and orientation of the knobs have been specially considered (p. 226). Contrary to general belief, striae formed during the earliest stages of the latest glaciation may be preserved where the conditions have been favorable. From knobs and scratches Dr. Ljungner has deduced several successive directions of the ice movements in the Scandinavian mountain range, which he names the "Scandes."

In the region studied there seem to be striae from five main directions, in chronological order from the northwest (*a*), the southeast (*b*), the east (*c*), the northwest (*d*), and the southwest (*e*) (p. 228). The oldest northwest striae and glaciated knobs are referred to Stage I of the glaciation of the Scandes. The ice was limited to the range but was thick and may have had a divide, which, part of the time, lay west of the watershed. From this time there are cirques on the east side of the mountains, suggesting by their elevations that the glaciation line lay 1,100–1,200 meters lower than at present (p. 230).

The southeast striae (*b*) in the Scandes are associated with the position of the ice divide at the Gulf of Bothnia during the maximum extent of the ice, Stage II. The greatest observed amount of glacial depression (or later uplift) of the earth's crust, 295 meters, is to be found on the Swedish coast near lat. 63° N.; but it seems probable that the site of the actual center of ice accumulation and of maximum crustal depression was considerably farther south (p. 233). The ice sheet may have culminated at separate times on the Atlantic and in the south and southeast. On the east slope of the Scandes the ice surface attained much greater altitude during this stage than during Stage I. Oscillations in the southern marginal belt of the large ice sheet would not be recorded in the Scandes and are not discussed by Ljungner.

A shift in the direction of the striae from the southeast to the east (*c*) indicates a northward migration of the ice center during a late stage of deglaciation, Stage III (p. 235). Still later the ice divide lay north of the area studied, on the east slope of the range, and the ice dammed up lakes on its west side.

During Stage I, precipitation and winds may have been about as today, but the temperature was lower (p. 236). The transition from Stage I to Stage II is not well understood, since the accumulation of ice on the range tended to sharpen the continentality of the lowland to the east and to favor foehn winds (p. 237). Winds, precipitation, and Gulf Stream are thought to have resembled those of today until the lowland was covered by ice. When the general temperature-lowering had shortened the melt-season so that part of the winter's snow persisted until the next winter, the greatly increased reflection of the solar heat by the snow may have further lowered the temperature, so that the permanent snow fields grew and the glaciation line sank. Piedmont glaciers then pushed over the lowland and formed the nucleus of the ice sheet. The origin of the snow is not discussed by Ljungner; but, if the snow was partly, perhaps largely, wind-drifted from the west side of the divide and partly locally precipitated, Ljungner's explanation of the transition does not differ much from those previously applied to the ices in Scandinavia and western Canada. Before long, an anticyclone formed over the ice and snow and grew in strength. The cyclone tracks over southernmost Scandinavia gained in importance at the expense of those over the northwestern part of the peninsula, and snow was precipitated on the Fenno-Scandian lowland, which was quickly flooded by ice (p. 238). The ice sheet grew to attain its maximum.

Since the most favorable temperature for snowfall is 32° F., a temperature-lowering causes the optimal zone of snowfall to move toward the Equator and downward in the mountains. Thus temperature-lowering was one cause for the southward spread of the ice. Another cause was the development of the anticyclone and the southward move of the cyclone tracks.

During the deglaciation, the ice center or ice axis shifted northwestward. Shortly before the end, the ice divide moved toward the Scandine watershed because the melting was asymmetrical, because the ice divide must be higher than the ice on either side, and because high-latitudinal cyclones grew in frequency and importance (p. 239). But, on account of a rapid temperature rise, the ice shed never reached the crest of the range, and the local glaciers were too insignificant to supply sufficient nourishment to the shrinking ice remnant.

The reviewer wishes to call attention to the analogy between the Nordic ice sheet and the Cordilleran-Keewatin ice of northwestern North America. Each started in a mountain range lying athwart the cyclonic paths on the west side of a continent. How the ice spread to the plains on the lee side and there accumulated to a huge ice sheet has not been adequately explained in either case. However, that the European ice sheet originated in the Scandes is obvious, for there was no other possible starting-point. That the Keewatin ice grew from the Canadian Cordillera and its ice is probable enough.

The Wisconsin glaciation had two separate maxima in western North America—the Iowan and the Mankato. The last Nordic glaciation also had widely spaced maxima, according to German geologists. Since the interval between the solar-radiation maximum, about 128,000 years ago, and the minimum, 116,000 years ago, may have been too short to permit the formation of a huge ice sheet, Würm 1 of the Germans may, at most, have been a mountain glaciation. Perhaps the glaciation of the Scandes was the correlative of Würm 1. Perhaps also the Warthe and the Weichsel continental glaciations were correlatives of the Würm 2 and Würm 3 and of the Iowan and the Mankato. The border of the Warthe glaciation runs west of Hamburg, north of Breslau, south of Warsaw and Minsk, through Moscow, and northeastward into Siberia (for Russia see R. F. Flint and H. G. Dorsey, "Glaciation of Siberia," *Bull. Geol. Soc. Amer.*, Vol. LVI [1945], pp. 89–106; Pl. I, "Latest Glacial Stage"). The border of the Weichsel runs east of Hamburg, south of Berlin and Posen, and in a bow through Russia and the Kanin Peninsula to Barents Sea.

A late paper by Ljungner ("Ein ostskandinavisches Vergletscherungsintervall," *Geol. Fören. Förhandl.*, Vol. LXVIII [Stockholm, 1946], pp. 81–86) makes it clear that the above-mentioned mountain glaciation, Stage I, which was of very long duration, immediately preceded the continental glaciation. But, separated from Stage I by an ice-free interstadial, there now seems to have been another, still older, glaciation, which then might be the correlative of Würm 1.

The comparison may be carried further. The greatest glaciation in northeastern Siberia (the latest one is not mapped but was small), as described and mapped by Flint and Dorsey (also G. B. Cressey, "Glaciation in Siberia," *Geog. Rev.*, January, 1946, pp. 159–60), may have resembled early stages of Labrador ices. Much or most of the moisture in northeastern Siberia came from the Sea of Okhotsk and the Bering Sea. Cyclonic storms from the distant Atlantic brought too little precipitation to permit the growth of a large ice sheet. Since storms could bring little if any moisture across a large Nordic ice sheet, the glaciations in Siberia are by some Russian geologists believed not to have been synchronous with the Nordic glaciations (Flint and Dorsey, p. 103). The last Labrador glaciation is held by the reviewer to have started rather late by moisture from the east and to have culminated in the interval between the Iowan and the Mankato maxima (*Amer. Jour. Sci.*, Vol. CCXLIII *A* [1945], pp. 1–39).

ERNST ANTEVS

Some Glaciomorphological Forms and Their Evidence as to the Downwasting of the Inland Ice in Swedish and Norwegian Mountain Terrain. (Swedish with English summary). By CARL M:SON MANNERFELT. (*Geografiska Annaler.*) Stockholm, 1945. Pp. 1–239; pls. 15.

This beautifully illustrated memoir is, first, a study of the erosional and depositional land forms which arose during the waning of the last remnants of the latest ice sheet in central Scandinavia, about 10°–14° E. and 62°–63° N. It is, furthermore, a study of the mode of the ice wasting in and near the final ice-divide zone and of the history of the last glacial epoch. Relatively continental climates in all the studied areas except Sylarna, together with the nature of the country rocks, have tended to preserve the topographic forms exceptionally well.

The glacial land forms distinguished are divided into supraglacial, lateral, subglacial, and frontal and extramarginal (pp. 211, 228).

Here only the most important ones will be mentioned.

As the ice melted down in the mountains studied, ablation moraine increased on the ice surface (p. 212). On modern glaciers, ablation moraine accumulates in strange shapes and at times becomes arranged in ridges parallel to the ice edge (pp. 12–14, 223). Thus a glacier with a thick moraine cover may advance suddenly over broken terrain, developing large concentric fissures, in which ablation moraine slips down. Englacial moraine beds, melting out along glide planes, may also form parallel ridges. The debris which slumped into depressions and crevasses in Scandinavia was ultimately deposited on top of the subglacial deposits (p. 212). Ablation moraine is here present, particularly in broad mountain valleys and on intermontane plateaus.

Lateral drainage channels are numerous in the lower continental parts of the Scandes (pp. 212, 224, 226, 228; maps; Pls. XII–XIV). They are about equally abundant in all exposures, showing that insolation was not a decisive factor in the melting. When occurring in numbers, one below the other, they indicate the yearly thinning of the ice. When strictly lateral, they also record the ice slope. Lateral terraces of accumulation, especially when long, are still better indicators of the mean slope of the ice (pp. 73, 76, 90, 167, 213).

Subglacial chutes are common features (pp. 215, 225). They were formed either as downhill branches of lateral drainage channels or as independent gullies or ravines, which cross these channels (Pls. III, IV, XIII). They arise especially when streams with relatively warm water melt their way under the ice (p. 23). In the center of the valley several may join to form a master-channel (pp. 23, 190; Pl. IX). In Oviksfjällen (pp. 76, 225; Pls. I, III), Fjätervåla (pp. 121–24, 226; Pl. VIII), and Sylarna (pp. 192–96, 228; Pl. IX) there are abruptly turning ridges descending the hill slopes. No similar formations seem to have been described. The Swedish name "slukås," suggested by Dr. Mannerfelt, has been translated as "subglacially engorged esker" (pp. 47, 225), but perhaps "chute esker" would be better. The ridges are commonly 2–6 meters high and 10–20 meters wide at the base, but a few attain a height of 8 meters (pp. 76, 123, 193). They consist of current-bedded sand and gravel with a thin mantle of bouldery till. The chute eskers occur in re-entrants or coves and below irregular precipices. They may have been deposited in tunnels below the ice, the sand and gravel by streams, the till shell by the melting ice. On the valley floor, chute eskers from the valley sides may join to form an axial esker (pp. 82, 149, 176). In other cases, tunnel fillings produce a network of esker ridges (p. 83; Pl. IV).

Between the mountains there are large areas of so-called "dead-ice" moraine, which is characterized by a maze of hummocks, crooked uneven ridges, and numerous depressions and kettles, many of which contain lakes or ponds (pp. 88, 143–58, 181–83, 197–201, 216, 225–28). Some of the ridges consist of a core of glaciofluvial sand and gravel veneered by ablation moraine, while others are composed entirely of till. Many ridges may have been formed in tunnels under dead ice, receiving the till mantle at the final melting of the ice. Others have been formed at the ice margin, but none have been pushed together. Undisturbed subglacial accumulations indicate that the marginal ice was stagnant (p. 216).

In the lower mountains near the ice-divide zone there are, in the cols between the summits, dry ravines or canyons cut usually in solid rock (pp. 33, 41, 128, 217, 224–26; Pls. I, VI, X). These are called "col gullies" in the translation, but perhaps "col ravines" would be more appropriate. Most of the ravines are from a few to 20 meters deep; but Dromskåran is a striking box canyon, 40 meters deep and 900 meters long (p. 53; Pls. II, XI). These col ravines must have been cut by glacial streams when the summits melted out of the sloping ice. Since the water postulates strong ablation, the névé line must have stood decidedly higher than any col ravine.

The frontal and extramarginal deposits on the valley floors and plateaus were conditioned by the slope of the ground and the state of the ice lobe (p. 217). In level terrain and gentle counterslope the ice was relatively solid, and hummocky dead-ice moraine was formed under and at the ice margin (p. 181). In broken terrain and on forward-sloping ground the ice gradually broke up at the same time that it grew thinner and terminated in a tapering, ragged, drift-covered margin (pp. 118, 218). Severing of ice blocks can have taken place through comparatively fast melting of relatively drift-free parts of the ice, through water erosion, formation of fissures, or free-melting of ice blocks in depressions (p. 27). The detached ice blocks partly controlled drainage and deposition, the

latter taking place on, between, and just outside the blocks (pp. 80, 114). Push moraines have not been observed in the area. On its west side the ice dammed up numerous lakes in which it ended in a calving cliff (p. 118). The lakes well to the west of the ice divide are floored by varved glacial clay, but those near the ice divide are normally not. These latter seem to have lost their sediments by sudden drainages, which perhaps occurred when the rising water floated the ice edge and ran off underneath (Fig. 4).

The névé or snow line—the boundary between accumulation and dissipation on a glacier—is largely a function of the snowfall during the season of accumulation and of the temperature during that of ablation (p. 8). A large ice sheet has its snow line near the margin and is nourished mainly in an inframarginal belt, which essentially controls the marginal movements of the ice. As long as there is an area of snow accumulation, there is outflow of ice. A dead-ice belt at a distance from the ice center means only that, because of some obstacle, ice flow has ceased in that particular region. When the snow line has withdrawn to the top of the ice (glacier, ice cap, or ice-sheet remnant) and ablation exceeds nourishment on the entire ice, this is climatically dead (p. 9). A climatically dead ice is not necessarily stagnant, for in subaquatic situations sudden drainages, exceptional calvings, or topographically conditioned severings of ice blocks can release outflow (p. 32). The ice is dynamically dead only when it has lost all motion.

Since the snow line is the upper limit of excessive melting, above it the glacier normally runs up on the bordering rock wall, while below it there is melted a trench between the ice and the wall (p. 10). Since the summits of Oviksfjällen, Sonfjället, and other mountains studied in Härjedalen and Dalarna when emerging as nunataks were encircled by open water, as shown by col ravines, they must already have been below the névé line (pp. 10, 32, 34, 100, 224, 226). The last ice-divide zone lay 20–40 kilometers to the south and southeast of Oviksfjällen, whose highest summit attains 1,370 meters (pp. 28, 224; Pl. I). Assuming a mean slope of the ice surface of 1 meter in 100 meters, the ice divide had an elevation of some 1,600 meters when Oviksfjällen began to appear as nunataks (p. 32). Since the late glacial snow line cannot have been lower than 1,500 meters in Sylarna and rose inland, the ice divide may have been below the snow line when Oviksfjällen began to melt out. Thus the entire regional ice remnant, which may have been 40–50 miles wide, was then climatically dead and undergoing wastage.

The decrease in ablation from the ice edge upward is shown by the decreasing slope of the ice surface. In Oviksfjällen a lateral terrace and a lateral drainage channel indicate a slope of 3 in 100 for the first kilometer and of about 1 in 100 in the second or third kilometer (pp. 72–74). Mannerfelt assumes generally for these mountains an ice slope of 3 in 100 at the edge, 2 in 100 a few kilometers from the edge, and <1 in 100 for the inframarginal ice surface (p. 225). The annual downmelting, as recorded by the vertical distance between lateral channels, averaged 5 meters (p. 74). This marginal thinning means a yearly retreat of the ice edge on level ground of 150 meters.

After Oviksfjällen had become exposed, ice lobes lingered in the lowest valleys to the east (p. 67). Subglacial chutes and chute eskers testify to thin and decayed ice (pp. 22, 225; Pls. I, III). Fantastic landscapes of pits, kettles, lakes, knobs, and irregular, frequently anastomosing ridges show that the ice lobes were honeycombed by tunnels, rent by fissures, and split into blocks, under, between, and above which assorted drift and till were accumulated (Pl. IV). In lakes, ponded by the ice, the front retreated by calving.

Lateral drainage channels also illustrate the attenuation of the ice margin in other mountains. Thus in Sonfjället, situated some 10 miles southeast of the ice-divide zone, the slope of the marginal ice averaged 3.5 in 100 and the yearly thinning 4 meters (pp. 28, 102–9, 226). The annual retreat of the ice edge consequently measured 100–150 meters (p. 111). In Idrefjällen of northern Dalarna the ice slope averaged >2 in 100 (pp. 120, 125, 126, 226). In Transtrandsfjällen the marginal ice slope was about 3.5 in 100, the annual lowering 3 meters, and the yearly recession 90 meters (pp. 129, 142, 226).

In all the regions mentioned, the mean slope of the ice surface in the belt of ablation seems to have been about 1.5 in 100 (pp. 111, 142), which equals 79.2 feet per mile, or almost 2,000 feet in 25 miles. With this slope the ice edge would have been some 50 km. (30 miles) distant, when the highest lateral drainage channels were formed in Sonfjället (p. 111), i.e., the zone of melting may have been 50 km. wide. Clearly, the belt of ablation was not very wide, and any

zone of severed ice blocks was narrow at any one time.

The introductory stage of the Last Glacial in Europe was a severe local glaciation in the high mountains of Scandinavia, as suggested in the present area by large, well-developed cirques in Rendalssölen (pp. 157, 227), Rondane (pp. 160, 168–70), and Sylarna (pp. 173, 187, 209; Pl. IX). The large size of the cirques, puny moraines if any, and terraces in some cirques clearly show that these were excavated before the culmination of the latest glaciation, not, as previously held, during its final stage. They may have been eroded at the beginning of this glaciation as well as during earlier glacials. A similar dating has long been given the cirques in the mountains of New England.

The next main stage was the development of the ice sheet which ultimately covered all northern Europe. This sheet seems to have conserved, rather than destroyed, the topographic features of the high mountains in the central regions, such as cirques and sharp ridges (pp. 169–71, 210).

Finally came the stage of ice wastage, from the last part of which derive all the mentioned land forms except the cirques. This was the end of the Last Glacial in the lower mountains (pp. 135–36, 156). Not so, however, in Rendalssölen (pp. 157–59, 227), Rondane (pp. 160, 168), and Sylarna (pp. 173, 187, 203–9, 228), where glaciers were reborn in some of the old cirques. These glaciers were small and short-lived, but they cleaned out the cirques and locally sharpened the features. Peat bogs inside moraines show that the glaciation antedated the warm age of the Postglacial (pp. 168, 204). At present, Rondane touches the glaciation line and has some névé fields (p. 161), while Sylarna have a small glacier (pp. 173, 187, 208; Pl. IX).

It is a careful, level-headed, and important piece of research, appropriately dedicated to the outstanding student of modern glaciers, Professor Hans Ahlmann.

Ernst Antevs

Geology of Lau, Fiji. By Henry S. Ladd and J. Edward Hoffmeister. (Bull. 181.) Honolulu: Bernice P. Bishop Museum, 1945. Pp. 399; figs. 41, pls. 62.

The 180th meridian divides the Fiji Islands into a western group, including Vitilevu and Vanualevu, which are much larger than all the other islands combined, and an eastern north-and-south belt of about one hundred small islands, known as Lau. An excellent treatment of the geology of Vitilevu appeared in 1934 as Bishop Museum Bulletin No. 119 by H. S. Ladd and collaborators. That same year a University of Rochester expedition made a careful study of twenty-six of the Lau Islands to supplement earlier investigations, to tie the geological history of Tonga (visited by Hoffmeister in 1926) to that of western Fiji, and to obtain data bearing on the coral-reef problem. The present volume is their matured report.

The oldest rocks found in Lau are andesitic pyroclastics and flows, widely exposed, and probably not greatly older than the Lower (or Middle?) Miocene Futuna limestone resting on them. The Futuna is dominantly a bedded formation, rich in algae and Foraminifera but poor in corals. Its deposition was followed by emergence and widespread erosion. Volcanism (agglomerates and lava flows, chiefly of olivine basalt) again set in during the emergence in later Miocene times. The Ndalithoni (Pliocene) limestone on the flanks of certain islands indicates resubmergence of parts of Lau at least. Intermittant uplifts followed the close of the Tertiary, while, during intervening times of standstill, wave erosion and reef growth formed terraces around the margins of the islands. Lavas (Mango odinite) reached the surface of two of the islands after they were elevated.

The report takes up each island in turn, giving in detail its descriptive geology, the interpreted geologic history, and, for many of the islands, comparisons with earlier interpretations, some of which are particularly helpful in acquainting the reader with the major problems involved and how they have been attacked. Earlier researches in Lau were chiefly those of J. Stanley Gardiner, Alexander Agassiz, E. C. Andrews, W. M. Davis, and W. G. Foye.

Recognition of widespread, uplifted Tertiary deposits is prerequisite to the interpretation of the physiographic features. Some of the land forms in the limestone areas are explained in terms of organic growth, whereas others are evidently the results of chemical and mechanical erosion. Wave attack is of great importance along the coasts; but inland, mechanical erosion is unimportant and completely overshadowed by solution. Normal valleys do not form in the limestone areas of Lau; instead, solution makes basins of all sizes and shapes, which dominate the topography. Under favorable conditions solution may continue for appreciable distances

below sea-level, for a lenticular mass of fresh water underlies each island.

The prevailing basin shapes of the small limestone islands in Lau led early investigators to interpret them as elevated atolls. Ladd and Hoffmeister's detailed studies indicate that, for certain islands, this interpretation is probably correct; but, on the other hand, the limestones of many other islands having well-developed basins do not show elevated reef structure to support the atoll hypothesis. Their basin shapes cannot be attributed directly to organic growth; apparently these islands rose from the sea as unrimmed, limestone-veneered banks; solution then produced pits and caverns whose coalescence has gradually developed the basin form.

Davis, having accepted Gardiner's view that the basin-shaped islands of eastern Fiji represent elevated atolls and recognizing different types of reefs in five belts, trending north-northwest and south-southeast, postulated "a westward migrating anticline on which the islands ride up and down like bits of driftwood disturbed by a wave from a passing steamer." While the distribution of reef types which led Davis to this hypothesis is very suggestive, as viewed on the chart, Ladd and Hoffmeister have a different interpretation and do not agree with him that only Darwin's reef theories explain the reefs of this area. They believe that "Lau's reefs, both Recent and elevated, can be most satisfactorily explained without any form of Darwinian subsidence." In their opinion, the evidence of widespread elevation (rather than a migrating anticline) cannot be ignored. They could find no thick elevated reefs to fit the subsidence theory; in fact, their studies of the elevated limestones show that "true elevated reefs are rare in Lau and that most of them were formed between periods of uplift." The authors, however, have not attempted in this volume to discuss, except incidentally, the controversial subject of the origin of coral reefs. That will be treated in a separate paper on the antecedent-platform theory which they support.

The volume also includes the following reports: "Petrography of Igneous Rocks," by Harold L. Alling; "Petrography of Limestones," by Geoffrey W. Crickmay; "Chemical Composition of Limestones," by J. W. Sanders and G. W. Crickmay; "Larger Foraminifera," by W. Storrs Cole; "Echinoidea," by Hubert Lyman Clark; "Barnacles," by H. A. Pilsbry; and "Decapod Crustacea," by Mary J. Rathbun.

Calcareous red algae were the most abundant contributors to the Lau limestones; second in importance were the Foraminifera, followed by corals, mollusks, echinoids, and brachiopods. Most of the dolomite is secondary, for it is found replacing fossils, such as corals, which are known to contain originally nearly pure calcium carbonate. But in a few places the lack of extensive alteration of the material strongly suggests that the calcareous mud contained a high percentage of magnesium when deposited. Sanders and Crickmay believe that many of the dolomites received their magnesia by replacement soon after deposition of calcium carbonate and think it "reasonable to suppose that this addition is greatest where sediments are accumulating very slowly and least where sediments are quickly buried and thus to some extent removed from participation in whatever chemical reactions effect the replacement."

The *Geology of Lau* is valuable as a regional study of this portion of the Fijian Archipelago. But its importance extends well beyond the reaches of these islands, for some of the trustworthy factual information here presented bears pointedly on several controversial geologic questions which can only be settled by an abundance of sufficiently representative established facts.

R. T. C.

Pyrites Deposits of Missouri. By OLIVER R. GRAWE. (Missouri Geological Survey and Water Resources, Vol. XXX [2d ser.].) Rolla, Mo. 1945. Pp. 482; pls. 17; figs. 8.

This report is in two almost equal parts. The first half includes ten chapters dealing primarily with the geological aspects of the pyrites areas, while the second half consists of one chapter devoted to the history and description of 91 mines and prospects.

Six districts have sufficient pyrites to have encouraged prospecting, but only two have produced commercial pyrites. By far the most production has come from deposits in hematite-bearing sink structures of the north central Ozark plateau. The greater part of the book is devoted to these occurrences.

In the area of sink structures, Grawe describes the physiography, stratigraphy, and structure. He considers the relationship of the "sulphur ores" to the controlling geologic factors.

There are three chapters on the mineralogy of the sink-structure deposits. Mineral determinations are often supported by tables comparing spacing and intensity measurements from X-ray diffraction patterns. The pattern measurements of the mineral in question is compared to those of a known mineral. The general mineral paragenesis is apparent from field work, but verification and added details were obtained from studies of polished specimens. Many good microphotographs are reproduced. Spectrographic analyses were run on 55 samples of pyrite, affording a basis for comparing pyrites within and outside Missouri. Twenty-six samples of the oxidized ore (hematite) were spectrographically analyzed to determine the changes in minor constituents due to oxidation.

The last chapter on pyrites deposits of the sink structures treats the origin of the structures and their fills. Previous theories are outlined, and a list is presented of thirty facts which any theory of origin must recognize. In the author's theory, basin-shaped caves developed above the ground water. These were filled with ground water by a slight depression of the north central Ozark region. This water "was somewhat saline and charged with hydrogen sulphide similar to the present ground water in the sediments beneath the Pennsylvanian formations off the Ozark dome." It was the source of the sulphur. The iron was leached from weathering Pennsylvanian and other sediments by surface waters and taken into solution as ferrous bicarbonate. "The sink structure .... acted as a large leaching basin or funnel" and guided the surface ferrous bicarbonate charged waters downward into contact with the hydrogen sulphide bearing ground water.

".... Iron was precipitated as pyrites in accordance with the following reaction:

$$2Fe(HCO_3)_2 + 4H_2S + O_2 = FeS_2 + 6H_2O + 4\,CO_2 ."$$

When Missouri pyrites mining was at the height of its third productive period (1934–40), Grawe collected the vital statistics of 91 mines and prospects. This information, recorded and evaluated in the second half of Grawe's report, will form a starting-place for any future development of the pyrites-mining industries.

Although Grawe's theory of origin for the pyrites deposits of the north central Ozark plateau seems adequate, his treatment of the basin-like sink structures in which these pyrites occur needs further attention. Formed in Ordovician cherty dolomite, they are elliptical in plan and are usually rimmed by overlying sandstone, which lines the upper part of the basin and dips inward with increasing steepness toward the center. The sink structures are more extensive horizontally and vertically than the pyrite deposits, which range in size from very small to several hundred feet across. In one deposit, "sulphur ore" was mined 325 feet beneath the surface. The sink basins are lined with chert conglomerate, which extends up under the sandstone rim rock and down beneath the bottom of the deposit. At a number of mines, masses of an Ordovician dolomite, which once overlay the sandstone rim rock, have been observed within the sink structure, and, in one mine, Pennsylvanian sandstone and clay-shales were also present.

The occurrence of Pennsylvanian strata in the pyrites-bearing sink structures calls to the reviewer's attention an older (1943) Missouri Bureau of Geology and Mines report, by H. S. McQueen, on the *Fire Clay District of East Central Missouri*. The fire-clay deposits of which McQueen writes are largely sandstone-rimmed sink structures filled with Pennsylvanian sediments. The deposits are generally small in the northern part of the district and larger in the southern part, where they reach the proportions of the pyrites-bearing sink structures just to the south. McQueen writes that, in his opinion, "the occurrence of iron ore in a district just south of the southern district in structurally similar, sandstone-lined sink-hole type deposits, is a manifestation of the lower part of a sink-hole type structure of which the clay bearing portion is the upper part." The sink structures of the fire-clay district are filled with Pennsylvanian shales, clays, sandstone, and some coal. These fills have "subsided" to their present position. In some cases more than one period of subsidence can be recognized. In many instances the fills have been faulted, folded, and brecciated in this process of subsidence.

Several years ago the reviewer visited one of these clay-filled pits near Stanton, Missouri, on the south side of Route 66. The pit is one of the larger sink structures. A lasting impression was made by a 1-foot bed of coal standing essentially vertical and forming a coal lining for at least half the circumference of the pit.

Both McQueen and Grawe think of these sink structures in terms of open caverns later filled by pyrites and/or clay. Grawe, in speak-

ing of the pyrites-bearing structures, says: "The bowl-like shape of many deposits suggests that vadose water played the dominant role in the development of the structure." As the water table was approached, the development of the cavity would be slowed up and ultimately stopped. "The result would be a subterranean room characterized by a rubble-covered floor, by a chert wall and by a sagged ceiling of dolomite and sandstone. This room would be at or near the center of a sink structure marked by gentle dips at the periphery, but changing abruptly to nearly vertical dips at the cavern wall."

The reviewer has explored many caves in Missouri and elsewhere. If any one thing stands out about caves, it is their linear extent. Isolated bowl-shaped caves are unknown to the reviewer. Floors may collect great rubble piles, but cherty dolomites do not produce chert concentrates on cave walls. Where sandstone roofs have been observed, they stand boldly in their stratigraphic position, until they partially or wholly collapse to add to the rubble floor.

McQueen, as well as Grawe, believes the sink structures developed above the ground-water table. However, Grawe records one sink structure which extends more than 325 feet below the ridge slope on which it is located, and many structures are recorded as occurring in present valley bottoms.

Since the present Ozark plateau has never been more deeply dissected than today, sink structures which extend below the present water table must have developed under phreatic conditions.

Grawe, in the study of the pyrites-bearing sink structures, uses the word "collapse" in many references to the anomalous stratigraphic position of some rock in the sink structures. McQueen, speaking of the clay-filled structures, also uses the word "collapse," but in some cases he modifies "collapse" by adding "or subsidence," and in many cases he refers only to "subsidence." Thus McQueen recognizes in the clay-filled sink structures a movement slower than that which might be supposed to follow collapse into open cavities.

In 1940, J H. Bretz published a paper in the *Journal of Geology* on "Solution Cavities in the Joliet Limestone of Northeastern Illinois." No reference is made to this paper by either Grawe or McQueen. The features which Bretz describes are elliptical, joint-controlled basins, ranging from a few feet to 150 feet in length and up to more than 40 feet in depth. The features diminish with depth and extend from the surface downward. The walls are a series of bedding-plane controlled moldings, which may overhang as much as 5 feet. All basins are filled with Pennsylvanian clays, with some sandstone and coal. In some basins the clay fill contains large blocks of Silurian limestone with a lithology that is not exposed in any of the basin walls, thus presumably coming from higher strata. The moldings of the basins in contact with the clay fill are slickensided on both upper- and undersides by motion of the fill down into the basin. Some small chert fragments from the clay fill mark the moldings with a long solution gouge, which leads to a small pit which still contains a chert fragment, imbedded in the limestone by the downward drag of the clay fill. The clay fill has been squeezed, faulted, brecciated, and sheared as it has pinched and swelled down into the irregularities of the basins. Sandstone lenses have been complexly folded and sheared, but not broken. A coal seam 1 foot thick, present as a horizontal bed on the flank of one of the basins, was traced down vertically as a thin pinching, swelling, and even overturned coal seam, $27\frac{1}{2}$ feet into the basin and then up on the opposite side to join its horizontal counterpart on the other flank of the basin. These and many other features indicated to Bretz that the invasion of the clay fill was very slow and that solution was going on at the clay-limestone contact while the fill was subsiding and was the cause of the subsidence.

Bretz concludes: "No pre-Pennsylvanian karst topography survives in these cavities. . . . . If there were sinks and caves at the time, they have since been modified by further solution under weight of overlying Pennsylvanian sediments which constantly subsided into the enlarging joint crevices."

The similarities of these solution cavities, except for size, to the sink structures of the Ozark plateau are striking. It may be possible that a better answer to the origin of the Missouri Ozark plateau sink structures can be found in a study of solution cavities in northeastern Illinois.

Aside from these considerations, Grawe's report is a comprehensive study on deposits which have had little previous attention. Both practical and academic, it is a valuable contribution to knowledge of Missouri geology.

PAUL HERBERT

Fortress Islands of the Pacific. By WILLIAM HERBERT HOBBS. Ann Arbor, Mich.: Edwards Brothers, Inc., 1945. Pp. 186; figs. 107. $2.50.

Professor Hobbs has long been a student of the Pacific islands and in 1921 made extended cruises in Japanese and American warships within the Japanese-mandated area, where he had exceptional opportunities to study and photograph many of the islands that have since been fortified. Recognizing the world-wide interest in the western Pacific awakened by the decisive campaigns conducted there and realizing the vital importance of many of these islands in plans for the future stability of our civilization, Professor Hobbs has brought together in very readable form the results of his own studies, supplemented by the principal pertinent facts obtainable from the scattered literature.

The author builds his book on geologic foundations, recognizing that the various modes of origin of the islands have determined in large part their special features and their military importance. They are divided, first, into "strewn islands" (primarily basaltic volcanoes, with or without capping organic reefs) and "arcuate islands," aligned along festoon-like mountain folds around the western borders of the Pacific. The reader gets the impression that the volcanoes of the strewn islands developed largely on land prior to a great sinking of the Pacific basin and submergence by that ocean. The alternative that they have been built up from the floor of the ocean by submarine lava outpourings is not mentioned. Sinking, however, harmonizes well enough with the Darwinian hypothesis for the origin of barrier reefs and atolls, the only coral-reef hypothesis here considered. This great subsidence of the Pacific basin is also held responsible for flexing the rising mountain arcs on the western margin of the basin. The surficial movement is pictured as being from the outer or convex side of the arcs, producing in front a trough or foredeep, next an upfold, which becomes inclined due to underthrusting if the process proceeds far enough, while volcanoes with characteristically andesitic lavas appear on the concave side of the arcs.

A chapter is devoted to each of the following types of "strewn islands": "Group Volcanoes (Hawaiian, Samoan islands, etc.)"; "Volcanoes (Eastern Carolines, Panape, etc.)"; "Almost-Atolls (Truk, Gambier, etc.)"; "Atolls (Kwajalein, Tarawa, Funafuti)"; "Part-raised Atolls (Wake, Christmas Island)"; and "Raised Atolls (Baker, Nauru)"; while two chapters each are given to "Newborn Arcuate Islands (Aleutians, Okinawa, Marianas, etc.)" and "Youthful Arcuate Islands (Yap, Bismarck, and Solomon archipelagoes, Fiji, etc.)." These constitute the major part of the book. They are concise, replete with interesting historical accounts and general information, and abundantly illustrated with maps and pen-and-ink drawings by the artist, W. B. Shaw, from the author's photographs. Brief discussions of "Catastrophic Visitations" (earthquakes, earthquake sea-waves, and hurricanes) and "Network of Essential Pacific Bases," with a classified Bibliography for further reading, complete the volume.

For anyone wishing a little essential information on the various islands of the Pacific, this will be a very useful reference book. The many maps of individual islands, atolls, or groups of islands are a commendable feature.

R. T. C.

Stratigraphy of the Marmaton Group, Pennsylvanian, in Kansas. By J. M. JEWETT. (State Geological Survey of Kansas, Bull. 58.) Lawrence, 1945. Pp. 148; pls. 4.

Rocks of the Marmaton group of Middle Pennsylvanian age outcrop diagonally across the southeast corner of Kansas in a belt about 100 miles long and 10–25 miles wide. They consist of various types of shale, limestone, and sandstone with a few thin coals, and they attain a thickness of about 250 feet. The group is divided into eight formations, which, in turn, are subdivided into nineteen named members.

This report is based on field work which began in 1928 and involved the tracing of numerous thin units across the state of Kansas and into neighboring parts of Missouri and Oklahoma. The attention given to details is evidenced by the 203 stratigraphic sections, measured to tenths of a foot or less, which constitute the last half of the bulletin. Such work in several states carried on during the last twenty years has entirely demolished the myth that the Pennsylvanian system is a hodgepodge of lenticular beds, few of which can be traced for any distance or correlated with any certainty. The continuity of some conspicuous Upper Pennsylvanian limestones in Kansas has long been known; but it is now evident that many thinner beds, some measurable only in inches,

are equally regular in their development throughout very wide areas.

The main part of the report is devoted to detailed descriptions of the various formations and members and is accompanied by four plates of correlated columnar sections, showing the developments of the four limestone formations and associated beds. It is a good example of the presentation of thorough and painstaking field work. Important though this may be to local geologists or specialists in Pennsylvanian stratigraphy, the concluding chapter entitled "Cyclical Deposits" is certain to be of much greater general interest.

After a review of present concepts regarding cyclic deposition, including a brief differentiation of cyclothems and megacyclothems and mention of the several theories that attempt to explain their formation, the cyclic repetition of strata within the Marmaton group is described. Four megacyclothems are recognized which consist of fifteen well-developed and several other poorly developed cyclothems. Different types of strata are contrasted, and explanations of their significance in the cyclical sequences are offered. Finally, the principal characters of the four megacyclothems and their subordinate cyclothems are presented.

J. MARVIN WELLER

Geology and Mineral Resources of the Jackson Purchase Region, Kentucky. By JOSEPH K. ROBERTS and BENJAMIN GILDERSLEEVE. Paleozoic geology by LOUISE BARTON FREEMAN. (Commonwealth of Kentucky, Department of Mines and Minerals, Geological Division, Ser. VIII, Bull. 8.) Frankfort, 1945. Pp. vii+126; figs. 21, with geologic map and correlation chart of the Tertiary, Kentucky–Alabama.

The Jackson Purchase region, acquired by the state from the Chickasaw Indians in 1818, includes eight counties at the western tip of the state, bounded on three sides by the waters of the Tennessee, the Ohio, and the Mississippi rivers. The publication dealing with the geology of this region is divided into five sections: an Introduction which gives the general geographic setting, a section on Paleozoic structure and stratigraphy, a third division devoted to Cretaceous stratigraphy, followed by a section on Tertiary stratigraphy, and a final section discussing the mineral resources of the area.

The only exposures of pre-Cretaceous rocks to be found in the region are confined to a narrow belt of Mississippian rocks adjacent to the Tennessee River at the extreme eastern edge of the map area. Virtually all the information on the stratigraphy and structure of the Paleozoic beds has been obtained from cuttings taken from oil test wells. Descriptions are given of Paleozoic formations from Middle Ordovician through Mississippian. Two structural maps have been compiled, one with contours drawn on the base of the Upper Cretaceous and the second on the top of the Everton (Chazyan). The structural picture is relatively simple, but considerable movement is indicated between Ordovician and Upper Cretaceous by the discordance of structures on the two maps. It should be pointed out that since the data for structural control are very limited because of the small number of wells in the area, the structure is likely to be far more complex than is indicated. Nevertheless, the information is sufficient to shed considerable light on the stratigraphy and structure of a region about which little has been known heretofore. It is the reviewer's opinion that Mrs. Freeman, who was responsible for this portion of the report, has made a significant contribution.

Most of the field work for the sections of the report dealing with Cretaceous and Tertiary stratigraphy was done by Roberts during the summer of 1929. Much of this material has been published in earlier reports. The author recognizes three formations in the Upper Cretaceous within the region, namely, the Tuscaloosa, the Eutaw, and the Ripley. He has divided the Tertiary and later into the Porters Creek (Midway) formation, the Holly Springs and Grenada formations (Wilcox), the Jackson formation, Plio-Pleistocene sand and gravel, and Pleistocene loessal deposits. Each formation, together with its structural features, is described in detail.

The section covering mineral resources was prepared by Gildersleeve and is devoted almost entirely (26 out of 32 pages) to the clay resources within the Cretaceous and Tertiary sediments. The various clay horizons are discussed, and detailed sections are given at localities where clays have been developed commercially. Tests on certain clays have been included, as well as flow sheets of operations where they are mined. Other resources of the area are discussed briefly.

The geologic map which accompanies the

bulletin has a scale of 2 miles to the inch and is reproduced in color, making a valuable addition to the report.

VINCENT E. NELSON

Geology and Mineral Resources of the Burkes Garden Quadrangle, Virginia. By BYRON N. COOPER. (Virginia Geological Survey Bull. 60.) Virginia: University, 1944. Pp. 299, figs. 11, tables 5, pls. 21, including geologic map and structure sections.

Burkes Garden is a topographic basin located in the Appalachians of western Virginia. Excavated on relatively nonresistant Ordovician limestones and clastics, it is almost completely encircled by erosional scarps, approximately 1,000 feet high and capped by Clinch sandstone. Structurally, the feature is an elliptical dome, 8 miles long and 4 miles wide, with its axis of elongation parallel to the general trend of Appalachian folding. Unique among the topographic-structural forms of the fold belt, Burkes Garden has given its name to a quadrangle which, except for 2 or 3 square miles in its northwestern corner, lies wholly within the faulted and folded Paleozoics comprising the so-called "Valley and Ridge Province."

Bulletin 60 of the Virginia Geological Survey, by Byron N. Cooper, offers a descriptive treatment of this quadrangle which will long serve as a standard of reference for workers in southern West Virginia, western Virginia, and eastern Tennessee.

Two-thirds of the 300-page text are devoted to stratigraphy. A foot-by-foot account of 17,000 feet of sediments ranging from the Rome formation (upper Lower Cambrian) to the Lee formation (Lower Pottsville) does not normally make exciting reading. Yet, by good writing, intimate knowledge of stratigraphy, not only of this quadrangle but of the central Appalachians, and a familiarity (which must have been acquired by long and critical study) with the work performed by other geologists in this region, Cooper manages to do the impossible, namely, to hold the reader's attention.

The stratigraphic section contains several features which are inherently interesting. Despite the high ratio of calcareous rocks, the area occupied an inshore situation throughout Paleozoic time, and the recurrent shifts of the strand line created a few surprising breaks in the section and a number of baffling changes in lithology and thickness within the limits of the quadrangle. Cooper does not fully appreciate the structural and geographic compression which the section has undergone, and it would be phenomenal if all his judgments on correlation are right. But he does demonstrate the need for caution in accepting the generalized correlations and nomenclature of some well known geologists who have sponsored most of the publications dealing with this and contiguous areas.

The reviewer is not qualified to judge all of the issues which Cooper has raised, but he must offer a criticism of the author's treatment of the Cliffield formation-group. In the central and northern parts of the quadrangle the Cliffield (lower Middle Ordovician) is 500 feet thick, and it thickens to approximately 800 feet southeastward. Where thin, it is divisible into five fairly persistent and differentiable units, which Cooper treats as "members" of the Cliffield "formation." Where thick, it is divisible into seven units, which Cooper dignifies as "formations" within the Cliffield "group." Four of the seven units are correlated from one section to the other, with minor changes in lithology and moderate variations in thickness. The reviewer can find no justification for altering the status of the Cliffield from a formation to a group, or of the members to formations. Although doing so may emphasize the marked stratigraphic change which occurs, the alteration injects unnecessary confusion into the nomenclature.

Aside from this single lapse, the complex problems and the endless details are masterfully handled. It is to be hoped that subsequent bulletins may provide comparable expository data which will make it possible to explain the changes and to verify the correlations from Tennessee to West Virginia and Pennsylvania.

Only 14 pages of the bulletin are devoted to structure, and the job is not too satisfactorily done. But the geologic map and the structure sections which comprise Plate I will provide material for hours of study. It is probable that the reader will prefer to reconstruct the ensemble of folds and minor faults in the individual thrust sheets which comprise the major structural elements of the Burkes Garden quadrangle, with no more than casual reference to the piecemeal descriptions of individual structures which Cooper contributes. He will certainly restore the structure of the Burkes Garden dome on some higher stratigraphic horizon than the Clinch in an effort to appreci-

ate the true stature of this interesting structure. He will also make some attempt to interpret the genetic relationships between the Burkes Garden dome and the curvature and tear faults along the Saltville-Bland fault to the south and the discontinuity in the fault to the north near the Narrows overthrust. Possibly Cooper was wise in restricting the text to exposition and in avoiding structural interpretations, which would inevitably become the subject of controversy. The geologic map and five structure sections constitute a major contribution to Appalachian orogenic phenomena, and it may be unfair to ask more of the author.

Cooper threads his way deftly through the maze of contradictions commonly known as "Appalachian geomorphology," making a few contributions that will stand amid the falling ruins of theory and speculation. Chief of the author's contributions is a brief analysis of the elevations of ridge crests in relation to the thickness and local structure of ridge-making formations. He comes out with the only possible conclusion, namely, that the elevations of essentially horizontal crests are a function of resistance, thickness, and dip, and not an index of cyclic erosion. Unfortunately, he goes somewhat beyond the conclusion warranted by his facts when he implies that denudation of horizontal surfaces on weak formations may likewise be noncyclic. Such an implication, however, can be supported by citation of good, if not reliable, authorities; and Cooper cannot be held for the solution of geomorphic problems on which all the doctors seem to disagree.

Following a brief but adequate treatment of the water resources and of the limited suite of rock and mineral products available in the quadrangle, Cooper concludes his volume with a résumé of the geologic history. As a summary of Paleozoic sedimentation, this section is good; but it follows the work of older geologists too uncritically in certain particulars. For example, this sentence (p. 280), "Toward the close of pre-Cambrian time, this region was worn down to an essentially base-leveled surface," will undoubtedly be read with general approval. On the same page, however, Cooper mentions that the Rome formation, the oldest exposed in the quadrangle, is underlain eastward by 1,000–1,800 feet of the Shady formation, "which in turn overlies several thousand feet of coarse sandstone and conglomerate of Chilhowee group."

These kinds of sediments do not accumulate to thicknesses of several thousands of feet on a base-leveled surface. Someday American geologists may attempt to reconcile the coarse clastic character of the Lower Cambrian series in the southern Appalachians; the thousand feet (and over) of relief at the base of the Cambrian in Wisconsin, Michigan, and Minnesota; and the hundreds of feet of relief on the pre-Cambrian floor in the Saint Francis Mountains of Missouri, the Black Hills of South Dakota, and the Adirondacks of New York, with the widely held concept of a late pre-Cambrian peneplain.

It is not fair to hold Cooper responsible for the mental lapses of his predecessors and contemporaries. He has done an excellent piece of areal and stratigraphic work, which it has been a pleasure to read and a privilege to review. It is commended to those who wish to understand the south-central Appalachians, as well as to those who wish to examine a model of one type of state-survey bulletin.

HOWARD A. MEYERHOFF

A Survey of Weathering Processes and Products. By PARRY REICHE. ("Publications in Geology," No. 1.) Albuquerque: University of New Mexico Press, 1945. Pp. 87; figs. 6. $0.75.

This book admirably describes and summarizes the various ways by which rocks are altered in weathering, "the response of materials which were in equilibrium within the lithosphere to conditions at or near its contact with the atmosphere, the hydrosphere, and .... the biosphere," and discusses the end-products of weathering, which are the source materials for sedimentary beds. Written by a geologist for geologists, it organizes present knowledge, chiefly from the sixty-seven papers included in the Bibliography, into a complete and clear outline of the subject, unobscured by too much descriptive detail. The author has not kept to the time-honored separation between soil-forming processes, due directly or indirectly to life, and inorganic weathering processes, since he believes the two are inseparably associated. The chapter on soil-forming processes should be of special value to the geologist, since in late years this study has been more and more divorced from our science, yet has many important geological aspects.

The book consists of five chapters, "Physical

Processes," "Chemical Processes and Reagents," "Results of Chemical Weathering," "Soil-forming Processes and Soils," and "Factors of Relief and Time."

The author concludes that purely physical processes of weathering are of secondary importance, only unloading and crystal growth being significant. Under chemical weathering, whose importance he considers "hard to overestimate," he discusses the fundamental laws and, in some detail, the roles in the weathering process of colloidal chemistry, hydration and hydrolysis, oxidation, reduction, and exchange reactions. The end-products of weathering are described, as well as the course of chemical weathering, with a discussion of studies on the relative mobilities of the chemical constituents of rocks and the relative stability and persistence of minerals. The discussion of soils is quite incomplete but probably adequate as an introduction to the subject. A brief discussion of peneplain soils is presented, and the laterite problem is succintly reviewed.

The book is a reference work which should be in every geologist's library; it can also serve as an introduction to the study of weathering and as a springboard to further study of the subject.

LOU WILLIAMS

The Snellius Expedition in the Eastern Part of the Netherlands East Indies (1929–1930) under Leadership of P. M. Van Riel, Vol. V: *Geological Results;* Part 3: "Bottom Samples"; Sec. I: "Collecting of the Samples and Some General Aspects." By PH. H. KUENEN. Pp. 46; figs. 6; pls. 2; tables 14. Sec. II: "The Composition and Distribution of the Samples." By IR. G. A. NEEB. Pp. 213; figs. 27; pls. 11; tables 32; maps 3. Leyden: E. J. Brill, 1942, 1943.

This report, which describes 382 samples collected by the Snellius Expedition, is divided into two sections.

Section I, by Kuenen, four chapters long, deals with the collection, treatment, and general interpretation of the sediments sampled. An improved Ekman sampler was used to secure most of the samples. Thinner walls and a more effective water-exit valve made possible the collection of longer cores. The organic content of the sediments averaged 1 per cent and varied directly with the clay content and depth of deposition and inversely with the lime content. Chemical analyses showed an abnormally high percentage of Na_2O. The radium content, however, is normal for deep-sea deposits, in spite of the unusually rapid sedimentation in the East Indian basins. The radioactivity is, therefore, a property of the sedimentary particles themselves; for, if the radioactivity were due to independent precipitation, it would be diluted and be lower than normal.

Kuenen discusses the anaerobic sedimentation in Kaoe Bay of Halmaheira Island and also the general absence of stratification and annual rhythms in the sediments of the whole area surveyed. The rate of postglacial sedimentation in the basins is estimated at 50 cm. per thousand years. Slumping and sliding of the sediments on the basin floors was found to be uncommon.

Section II, by Miss Neeb, contains eight chapters and comprises four-fifths of the report. The sediments sampled were classified into six major groups; globigerina ooze, red clay, coral mud and sand, terrigenous mud, volcanic mud, and volcanic plus terrigenous muds. Samples from earlier expeditions in the area, namely, the Cachelot, Challenger, Gazelle, and Siboga, were reinterpreted to conform to the above classification. A lengthy description of the mechanical and mineralogical composition of the individual samples is accompanied by many tables of grain-count results. Certain mineral suites of volcanic muds were found to be diagnostic of individual volcanos. On the basis of both light- and heavy-mineral studies, the terrigenous muds were subdivided into five groups, depending on whether the detrital constituents were derived from crystalline schists, acid igneous rocks, intermediate to basic metamorphic rocks, quartziferous sediments, or old volcanic rocks.

The results of Miss Neeb's detailed microscopic work and that of earlier surveys is embodied in a 1:4,000,000, six-color chart (about 24×24 inches), showing areal extent of the sediment types. Maps depicting the distribution of Tambora volcanic ash and the relative lime content of the sediments also accompany this report.

From volcanic-ash horizons of known age, the rate of accumulation of terrigenous muds was calculated to be 65 cm. per one thousand years, a rate fifty times that found by Schott for the Atlantic. The rate for globigerina ooze of 1 cm. per one thousand years agrees with Schott's determination.

The X-ray analyses of the mud fractions of several samples revealed a decrease in contents of quartz, muscovite, and feldspar and an increase of montmorillonite with a decrease in grain size.

Calcareous and siliceous organisms of the sediments are briefly treated. Miss Neeb can see no reflection of Pleistocene climate in the faunas of the sediments sampled.

The last chapter is devoted to the secondary minerals encountered. The pyrite content was found to be unrelated to depth of deposition and directly proportional to the carbon content.

An extensive Bibliography, together with a list of earlier publications concerning the Snellius Expedition, accompanies this report.

ROBERT NANZ

The Charnockite Rocks of Mysore (Southern India). By B. RAMA RAO. (Mysore Geological Department, Bull. 18.) Bangalore, 1945. Pp. iv+199; pls. 14. 3 Rs.

"Charnockite," a term originally used by Sir Thomas Holland to designate a variety of hypersthene granite, was later applied by him, in the expression "charnockite series," to a series of Indian rocks associated with the original charnockites and showing every gradation from granite through intermediate and basic types to ultrabasic types, all characterized by the presence of hypersthene. Similar rocks have since been described from widely separated regions of the earth, and there has been much controversy as to whether they represent a series of igneous differentiates, as Sir Thomas supposed, or whether some varieties represent metamorphosed (soaked) sedimentary material.

Rao now gives the results of a prolonged study of such rocks occurring in Mysore and constituting a northerly extension of the type areas. He concludes that the complex embraces a series of ancient sediments with intercalated sills and sheets of intrusive basic igneous rocks, showing notable differentiation and reaction effects with the sediments. Into this complex was intruded granitic magma, which greatly modified the older rocks, largely by soaking, and was itself modified by contamination with basic material, with consequent production of the intermediate and acid types of the charnockites.

N. L. B.

Bibliography on the Petroleum Industry. By E. DEGOLYER and HAROLD VANCE. (Bulletin of the Agricultural and Mechanical College of Texas, Fourth ser., Vol. XV, No. 11.) College Station, Tex., 1944. Pp. xxxii+730. $3.00.

The *Bibliography* was assembled from DeGolyer's personal files, the bibliography of the Petroleum Engineering Department at the Agricultural and Mechanical College of Texas, and a complete bibliography on the air-gas lift furnished by S. F. Shaw.

The references are listed in chronological order under approximately nine hundred headings, arranged according to a decimal system of classification. The major subject groupings are: (1) "General Data on Petroleum and Related Industries"; (2) "Geographical Distribution of Petroleum, Oil Fields, Properties, and Districts: Descriptions and Maps"; (3) "Physical and Chemical Properties of Petroleum, Examination, Testing, and Sampling"; (4) "Exploration and Prospecting for Petroleum and Other Bitumens: Geology of Petroleum"; (5) "Development of Deposits of Oil, Gas, and Other Bitumens"; (6) "Production of Petroleum and Natural Gas and Related Hydrocarbons"; (7) "Transportation, Storage and Gauging of Petroleum and Natural Gas"; (8) "Oil Refineries, and Refinery Practice"; (9) "Utilization of Petroleum and Its Products"; (10) "Economics of the Petroleum Industry."

The book contains a decimal index as well as an alphabetical subject index.

CHESTER JOHNSON

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FRESH- AND BRACKISH-WATER VERTEBRATE-BEARING DEPOSITS OF THE PENNSYLVANIAN OF ILLINOIS

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ABSTRACT

Vertebrate remains from the Pennsylvanian of Illinois have been obtained from deposits of the following types: red beds, sandstone channel fills, gray clays, including nodule-bearing beds associated with coal, black carbonaceous shales, and coal. The types of vertebrates recovered differ widely with the conditions of deposition. This is shown in a review of well-known localities for which new faunal lists are given, based on recent revisions, and of studies of new localities. Additions to the known Pennsylvanian faunas have come from the new localities. The fish faunas are shown to be close to the descendant Permian faunas. Analysis of the tetrapods, which are principally amphibians, emphasizes the inadequacy of the knowledge of amphibians and reptiles from typical Pennsylvanian deposits. It is probable that future work in Illinois will add to the knowledge of the Pennsylvanian vertebrates of the state but the chances of discovering extensive deposits containing well-preserved vertebrates appear to be remote.

INTRODUCTION

THE SCOPE OF INVESTIGATIONS

Scattered occurrences of vertebrates in fresh- and brackish-water Pennsylvanian beds in Illinois have been reported since the middle of the nineteenth century. Two localities, one near Oakwood variously called the "Danville locality" or the "Vermilion County locality" and one at Mazon Creek and vicinity, have received the attention of a large number of paleontologists. These finds and various reports of vertebrates in other nonmarine beds prompted the writer to search for additional localities in an effort to obtain better understanding of the fresh-water and terrestrial vertebrates of the Pennsylvanian. It was hoped especially that new finds of tetrapods might be made. These efforts have met with only moderate success but the possibilities of the state are not exhausted, and it is anticipated that this work can be carried on in future field seasons.

The type of deposit in which the Oakwood locality specimens occurred seemed to offer the most promising avenue of approach, but, as discussed more fully under the section entitled "Red Beds," this study has as yet yielded no positive results. It was considered futile to attempt to search the Mazon Creek type deposit for vertebrates. The fossils, which are predominantly plants, occur in ironstone nodules. Vertebrate remains are rare, and satisfactorily preserved specimens are found only very occasionally. Almost all recorded specimens have been found by persons searching for paleobotanical materials. No effort has been made to obtain new specimens from this series of localities.

Since exposures of the Oakwood type had little to offer and a search of the Mazon Creek area was deemed futile, investigation was directed toward a study of channel deposits which occur at several places in the state. The channel deposits which have been visited suggest that exploration of these sands and conglomerates offers a fruitful field for research. One, the Falmouth Channel, described in a later section, has yielded a fairly large number of specimens. A second, the Salt Fork Channel, has yielded fragments. Other channels, one in Vermilion County and one near Mazon Creek, have proved to be barren of fossils. As additional deposits of this type are located and studied important additions to the Pennsylvanian vertebrate fauna may be expected.

TYPES OF VERTEBRATE-BEARING BEDS

RED BEDS

The red beds of Illinois are sufficiently widespread and so similar in appearance to red beds of other areas which have produced vertebrate faunas that they are worthy of special consideration. The beds which yielded the Oakwood specimens have been called red by some students. There is, however, considerable confusion concerning them. E. D. Cope[1] mentioned them as dark gray and black shale. Gurley, who collected the bulk of the material, spoke of the beds as gray. R. L. Moodie,[2] who visited the locality and carried on relatively unsuccessful excavation, described the beds as red and gray shales. Wanless, in a personal communication, states that the beds are mottled red and gray. The writer has visited the locality several times and, although the precise position of the deposits was not seen, being apparently covered by slump, the horizon is clearly one of red and gray mottled shale. It is clear that the bones and teeth were associated with red shales although they may have come from the gray or black parts of the bed. Some of the bones show brilliant red stains and others are enclosed in a gray, nodular matrix.

There are several exposures of similar deposits in the vicinity of Oakwood. The writer, accompanied and aided by Dr. Ernest P. Du Bois, then of the Illinois State Geological Survey, visited these in an effort to determine whether or not they contained any traces of vertebrates. The results were negative. During the exploration samples were collected and studied to determine whether or not they contained any organic remains. No microfossils were found in any of the beds. The red shales of the state, however, are not uniformly barren of microfossils. One near La Salle, for example, yielded the following ostracodes: *Cavellina edmistonae* Kellet, *C. nebrascensis* (Geinitz), *C.* cf. *fittsi* Kellet—young molts, *Bairdia marmorea* Kellet, *B. hoxbarensis* Harlton, and *Cytherella symmetrica* Payne. In addition, there are numerous fragments of conodonts and small echinoid spines. This particular red shale is clearly marine. The lack of microfossils in some red deposits such as those in the area around Oakwood and the presence of terrestrial forms in some concentration in the Oakwood bone bed suggest that some of the red beds may be, in part at least, nonmarine.

The resemblance of the red shales of central Illinois to those of the Arroyo Formation in the Clear Fork of Baylor County, Texas, is striking. To some ex-

[1] "On the Fossil Remains of Reptilia and Fishes from Illinois," *Proc. Phila. Acad. Nat. Sci.*, Vol. XXVII (1875), pp. 404–11.

[2] "The Coal Measures Amphibia of North America," *Carnegie Inst. Wash. Pub. No. 238* (1916), p. 9.

tent, as well, there is a similarity of stratigraphic sequence, although comparisons cannot be carried too far. The usual sequence in Illinois, as observed in several localities, is limestone, a foot or two thick and with marine fossils, gray shale, unfossiliferous or nearly so, red shale, gray to green shale, and a capping sandstone. This pattern varies somewhat, especially in the thickness of the various members. The upper sandstone may be absent and the gray shale may grade into a calcareous member and then into pure limestone. A somewhat similar sequence is encountered in the Mabelle limestone and the overlying basal Arroyo beds north of Mabelle, Texas. The fossiliferous limestone is followed by gray shales which pass into red shale. Here, however, the resemblance ends, for the red shales, varied by the presence of channel sandstones and fine conglomerates, lenticular masses of sandstone and windblown sands, persist. They clearly represent terrestrial conditions which appear to have been introduced with the deposition of the red shales. Whatever terrestrial conditions may have existed in Illinois during the deposition of the red shales were short lived, for there is rapid return to marine conditions with deposition of new limestones. At the Oakwood locality the sequence, which includes red beds, is repeated twice in a section about 40 feet thick.

In the Arroyo red beds, large areas are totally unfossiliferous and fossils commonly occur in pockets. The Oakwood locality suggests that Illinois may be similar, with the added difficulty that the vertical range of the red members is limited. If this is the case, it may be anticipated that additional pockets of vertebrates may someday be found in the red beds and associated gray shales of the state. That possibility hinges primarily upon how much of the red shale was deposited under nonmarine conditions. At present this cannot be determined with any degree of certainty.

CHANNEL SANDSTONES

As a rule it is difficult to be absolutely certain that the sandstones commonly called channel fills were actually deposited under stream conditions. There is, in addition, some difficulty in determining whether these deposits were made by water flowing on the land or in shallow marine waters. The following criteria aid in these determinations: the bedding of the sandstone is irregular; the lateral extent of the beds is limited; there are conglomeratic lenses in some of the deposits; marine invertebrates occur in some of the sandstones; fresh-water fish have been encountered in all cases where vertebrates have been found; marine shark teeth have been found in at least one of the channels. These facts strongly suggest running water, and the limited lateral extent suggests localization in a channel. The rather uncommon marine fossils give some indication of deposition under marine conditions, but it is entirely possible to explain them as erratics derived from pre-existing marine deposits which have played a part in the formation of the channel deposits.

As yet it has been impossible to trace any one of the vertebrate-bearing sandstones sufficiently far to demonstrate by shape alone that it is a channel deposit, but, in view of the nature and relationships of the materials, the conclusion seems inescapable. The deposit at the Falmouth locality (see p. 290) lies directly on a limestone, the massive sand of the channel being separated from the limestone by about three inches of soft, sandy shale. The Salt Fork deposit (see

p. 296) rests on a typical gray Pennsylvanian shale. In both cases there is a sharp break between the underlying bed and the supposed channel deposit. In both cases the contact between the two beds is irregular and gives definite evidence of an erosional unconformity. Other channels which have been visited are similar in nature but have not yielded vertebrate remains. The extensive channels represented by the Pleasantview sandstone have not as yet been thoroughly explored for vertebrates, but no remains have been reported from them.

Vertebrate remains are not scattered at random through the channels, for much of the sandstone is barren. The thin, shaly layer at the base of the Falmouth Channel carries most of the remains found at this locality, but some bones occur in the lower part of the more massive overlying sandstone. In the Salt Fork Channel the vertebrate fragments have come only from a lenticular, semiconglomeratic mass near the base of the deposit.

BLACK CARBONACEOUS SHALES

The black carbonaceous shales of the coal measures have been discussed fully in many papers and merely need to be mentioned in this report. The invertebrate fauna which they contain is not a typical marine fauna, for it contains *Orbiculoidea* and conodonts and reflects somewhat unusual conditions of deposition. Many of the shales contain abundant fish remains, among which *Petrodus*, *Lystracanthus*, and *Edestus* predominate. These three types, which may not be generically distinct, are present in other deposits which have been interpreted as originating in brackish waters. No tetrapods have been found in the black shales. One lung-fish tooth, *Proceratodus carlinsvillensis* Romer and Smith, is reported to have come from black shale, but the matrix of the specimen suggests that it was in an impure coal. This is noted under the discussion of occurrences in coal.

GRAY SHALES

Most of the gray shales in the Pennsylvanian of Illinois appear to be marine and many of them carry marine invertebrates. Some which are closely associated with coal, such as those in the vicinity of Mazon Creek, carry nodules which enclose remains of fresh-water and terrestrial animals. A limited number yield nonmarine vertebrates deposited under other conditions. Two such localities are discussed in this paper, one on Piasa Creek, Jersey County, and a second in Marion County. There are no known sedimentological characteristics of these shales which indicate whether they are marine or nonmarine, so that fossils alone form the basis for determination. In the Piasa Creek locality organic remains are preserved for the most part in phosphatic nodules. Supposedly fresh-water fish are represented by rhipidistians, whereas the remaining vertebrates are sharks of the types which occur in the black fissile shales and marine limestones. A single specimen of *Xenacanthus* was obtained by J. M. Weller from the Marion County locality. It came from a gray shale rich in plant remains.

COAL

The richest fauna of Pennsylvanian vertebrates in the United States has come from a cannel coal at Linton, Ohio. No comparable localities have been found in the state of Illinois. Near Peoria, in "Coal Number 4" of the lowest McLeansboro age, there has been found the cranial roof and a tooth of *Sagenodus*

serratus (Newberry).[3] This deposit has yielded nothing more, perhaps more because of lack of study of the coal as it was mined than because of an actual lack of preserved vertebrates. A highly carbonaceous shale at Carlinsville, Illinois, which, from the matrix on the specimen, appears to be closer to coal than to shale, has yielded the holotype of *Pr. carlinsvillensis* Romer and Smith.[4] Both of these specimens were collected prior to 1900 and are part of the Gurley collection at Walker Museum. For the most part, the coals of Illinois have not furnished much information concerning the coal-swamp vertebrates of the Pennsylvanian.

THE LOCALITIES AND THEIR FAUNAS

In the following pages important localities in the state are described, and particular attention is paid to the faunas which have come from them. Where necessary, additional information concerning modes of occurrence is presented. It will be noted that the differences in faunas appear to be primarily a function of the environments of deposition.

THE OAKWOOD LOCALITY

This locality, variously called the "Danville locality," the "Vermilion County locality," and the "Oakwood locality," lies along the northern margin of Horseshoe Bend of the Vermilion River in the SE. $\frac{1}{4}$ SE. $\frac{1}{4}$, Sec. 23, T. 19 N., R. 13 W. of Vermilion County, Illinois. The general nature of the deposits has been discussed on pages 282 and 283.

E. C. Case,[5] in a report on this locality summarizing the work of E. D. Cope,[6, 7, 8] lists ten genera and twenty-two species of fish, amphibians, and reptiles as follows:

Fish
- *Janassa strigilina* Cope
- *J. gurleyana* Cope
- *Pleuracanthus quadriseriatus* (Cope)
- *P. gracilis* (Newberry)
- *P. compressus* (Newberry)
- *Thoracodus emydinus* Cope
- *Sagenodus vinslovii* (Cope)
- *S. vabasensis* (Cope)
- *S. gurleyanus* (Cope)
- *S. pusillus* (Cope)
- *S. fossatus* (Cope)
- *S. heterolophus* (Cope)
- *S. paucicristatus* (Cope)
- *Peplorhina arctata* Cope

Amphibians
- *Cricotus heteroclitus* Cope
- *Cr. gibsoni* Cope
- *Cr.* sp.
- *Diplocaulus salamandroides* Cope
- *Lysorophus tricarinatus* Cope

Reptiles
- *Clepsydrops colletii* Cope
- *Cl. pedunculatus* Cope
- *Cl. vinslovii* Cope
- *Archaeobelus vellicatus* Cope

This list may be taken as a point for departure in consideration of the fauna of this pocket, for it represents the first in which the animals were listed together. Earlier names, applied to certain of the genera, and Cope's revisions of the first-given names may be found in Cope's papers of 1875 and 1877. Various writers dealt with particular specimens between

[3] A. S. Romer and H. J. Smith, "American Carboniferous Dipnoans," *Jour. Geol.*, Vol. XLII (1934), p. 710.

[4] *Ibid.*, pp. 714–16.

[5] "The Vertebrates from the Permian Bone Bed of Vermilion County, Illinois," *Contr. Walker Mus.*, Vol. I (1901), pp. 3–29.

[6] Pp. 404–11 of ftn. 1 (1875).

[7] "On the Vertebrata of the Bone Bed of Eastern Illinois," *Proc. Amer. Phil. Soc.*, Vol. XVII (1877), pp. 53–64.

[8] "Descriptions of Extinct Vertebrata from the Permian and Triassic of the United States," *Proc. Amer. Phil. Soc.*, Vol. XVII (1877), pp. 182–93.

1875 and 1901, but few fundamental modifications of Cope's earlier determinations were made. Since 1901 others have considered the fauna as a whole or in part. The tendency has been to reduce the number of genera and species.

L. Hussakof[9] considered the fish in some detail. He retained the two species of *Janassa* on the grounds that their identity could not be demonstrated, since the two type-teeth, *J. strigilina* (W. M. 6500) and *J. gurleyana* (W. M. 6501), were from different parts of the mouth. There seems, however, no valid reason for assuming the two to be different, since it is now known that variation of the teeth in a single species is greater than that between these two. Both teeth may be referred to the first-named species *J. strigilina*. *T. emydinus* was considered by Hussakof as too incomplete to stand as the type of a genus. It appears to be a specimen of *Janassa* whose species cannot be determined.

A study of the three species referred by Case to the genus *Pleuracanthus* leads to a somewhat vexing taxonomic situation. Cope originally designated two sets of spine fragments as *Orthacanthus quadriseriatus* and *O. gracilis*. He referred a series of small teeth to *Diplodus* (?)*compressus* (Newberry). He was of the opinion that the teeth might actually belong to one of the species of *Orthacanthus*. This group at best is certain to lead into taxonomic difficulties because specimens are known variously from teeth, spines, parts of chondrocrania, and parts of the postcranium. It demonstrated, however, early in the history of the group that certain types of teeth and spines were associated, and failure to take cognizance of this early work has lead into more trouble than was necessary. The literature concerning Cope's specimens, as well as many others, is confusing.

Cope,[10] in 1883, replaced the name *Diplodus* with a new generic name *Didymodus* on the basis that *Diplodus* was preoccupied. Case,[11] in 1901, clarified the situation by referring all of the species from Oakwood to the genus *Pleuracanthus* Agassiz. The name of *Pleuracanthus* as applied to this type of shark by L. Agassiz[12] in 1837 is, however, invalid since it was preoccupied by *Pleuracanthus* Gray,[13] a generic name given to three species of Brazilian beetles in 1832. E. Beyrich,[14] in 1848, considered specimens of *Pleuracanthus* Agassiz and *Orthacanthus* Agassiz and other related types at some length. Inasmuch as he gave an adequate description of the genus *Xenacanthus*, which he proposed in this paper with *X. decheni* (Goldfuss) as his genotype, and also recognized the identity of *Pleuracanthus* Agassiz and *Xenacanthus*, his name may be considered to be valid and to replace *Pleuracanthus* (see O. P. Hay.)[15] Thus Cope's three species, if Case's lead in considering them generically identical be followed, may be called *X. ?compressus* (New-

[9] "Discussion of the Fossil Fishes," in E. C. Case, "Revisions of the Amphibia and Pisces of the Permian of North America," *Carnegie Inst. Wash. Pub. No. 146* (1911), pp. 155–75.

[10] "On some Vertebrates from the Permian of Illinois," *Proc. Phila. Acad. Nat. Sci.*, Vol. XXXV (1883), p. 108.

[11] Ftn. 5 (1901).

[12] *Recherches sur les Poissons Fossiles*, Vol. III (1837), p. 66.

[13] E. Griffith-C. Cuvier, *The Animal Kingdom* (London: Whitaker, Treacher & Co., 1832), Vol. XIV, p. 172.

[14] "Ueber *Xenacanthus Decheni* und *Holacanthus gracilis*, Zwei Fische aus der Formation des Rothliegende in Nord-Deutschland," *Arch. Min. Geogn. Bergb.*, Vol. XXII (1848), pp. 646–54.

[15] "Second Bibliography and Catalogue of the Fossil Vertebrata of North America," *Carnegie Inst. Wash. Pub. No. 390*, Vol. I (1929), p. 537.

berry), since Newberry's genus *Diplodus* must be replaced by *Xenacanthus*, *X. quadriseriatus* (Cope) and *X. gracilis* (Newberry). While this resolves the case of the Oakwood species, it does not clarify the status of various other genera and species of the *Xenacanthus* group.

In 1884, Cope[16] described as *Didymodus* a specimen from the Permian of Texas consisting of a chondrocranium. He apparently referred it to Newberry's species *Dip. compressus* (Newberry). S. Garman,[17] in 1885, in a paper in which he pointed out among other things that Cope's specimen clearly was not congeneric with his genus *Chlamydoselachus* as Cope had suggested, said that *Didymodus* was a synonym of *Xenacanthus* and thus invalid. He further stated that Cope's specimen was not *Xenacanthus*, as Cope himself (using the name *Pleuracanthus*) had intimated. Garman proposed the name *Diacranodus* and recognized the species *Dia. compressus* and *Dia. platypternus*. His procedure in using the specific name *compressus*, which appears to be a retention of the name as originally used in *Dip. compressus* Newberry, is questionable. If *Didymodus*, which replaced *Diplodus*, is a synonym of *Xenacanthus*, then Newberry's species must be referred to *Xenacanthus*. Garman indicates, following Cope, that *Diacranodus*, his new genus, is not the same as *Xenacanthus*. Had Garman indicated that he was naming a new species of the genus *Diacranodus* and had any description or definition of the species been given, the species might be acceptable. But Garman did neither. Cope,[18] in 1890, proposed the specific name *texensis* for the Texas specimen to replace *compressus* as used in *Did. compressus* (Newberry) and in *Dia. compressus* (Newberry). This species may be considered as valid replacing *Dia. compressus* as used by Garman. Whether the species is to be referred to *Xenacanthus*, on the basis that *Didymodus* is a synonym of *Xenacanthus*, or to *Diacranodus* must be determined by morphological comparisons.

The generic name *Diacranodus* may be considered valid if the generic separation from *Xenacanthus* can be demonstrated. Hussakof[19] accepted the name, indicating that the differences in the chondrocrania of *Xenacanthus*, for which he used the name *Pleuracanthus*, and *Diacranodus* are sufficient to make the separation valid. In essence this separates the Texas Permian specimens from these of the Carboniferous and earlier deposits. It is not, however, entirely satisfactory, since it is necessary to compare chondrocrania to determine the genus to which various specimens belong and only in rare instances is this possible. Furthermore, the differences in chondrocrania are slight and of questionable value for generic separation. Differentiation on the basis of teeth and spines is not feasible with the materials now known, and it seems improbable that teeth, at least, will ever furnish an adequate basis. This is true not only for specimens referred either to *Diacranodus* or *Xenacanthus* but also for various other named genera, *Protodus* Woodward, *Thrinacodus* Newberry, *Compsacanthus* Newberry, *Doliodus* Traquair, *Dittodus* Owen, *Orthacanthus* Agassiz, and others. It is true that teeth referred to various genera

[16] "The Skull of a Still Living Shark from the Coal Measures," *Amer. Nat.*, Vol. XVIII (1884), pp. 412–13.

[17] "*Chlamydoselachus anguineus* Garm.—a living species of Cladodont shark," *Bull. Mus. Comp. Zoöl.*, Vol. XII (1885), pp. 1–35.

[18] *Trans. Amer. Phil. Soc.*, new ser., Vol. XVI (1890), p. 285.

[19] P. 159 of ftn. 9 (1911).

in some instances show differences which might reflect generic distinctions, but a survey of the literature shows the confusion of reference which has occurred, indicating that in many instances definitive characters were at best vague.

Since generic differentiation on the basis of teeth and spines is unsatisfactory and since the differences between other characters of known specimens are not great, a practical working basis can be established by referring all these related forms from the Devonian through the Permian to a single genus *Xenacanthus* Beyrich. In so doing it must be realized that this genus contains a large and somewhat varied series and that the genus is not entirely commensurate with many genera defined on the basis of more adequate materials. But, under the circumstances, it is the only procedure which establishes a working basis for differentiation of the various xenacanthid sharks. In no case are the differences between known parts of the fishes sufficiently great that such an assignment does real violence to the concept of the genus. Throughout the pages of this paper we shall use this scheme of reference to and differentiation of the xenacanthids.

Hussakof,[20] in 1911, indicated that *T. emydinus*, which Woodward has called an incomplete tooth of *Janassa*, is too fragmentary to stand as a valid genus. The specimen is lost, but the illustrations show that Hussakof was entirely justified in his stand.

Case[21] referred all the lungfish of the Oakwood locality to the genus *Sagenodus*, following S. Woodward's[22] work of 1891. Cope originally recognizes the genera *Ctenodus* and *Ceratodus*. Romer and Smith,[23] in 1934, referred all specimens, originally differentiated into seven species, either to *S. serratus* or *S. paucicristatus*. The latter species is represented by one tooth, more elongated than the rest. Romer and Smith expressed the opinion that it is close to *S. copeanus* (Williston) and *S. porrectus* (Cope).

Cope[24] described a small tooth-studded plate (W. M. 6511) under the name of *Pe. arctata*. That a specimen so fragmentary should have been made a genotype is somewhat unfortunate. Cope first referred it to the Crossopterygia and later[25] called it a thermorphous reptile. Case,[26] while suggesting the possibility of cotylosaurian affinities, used a second specimen for comparison and concluded that the relationships were with the Crossopterygia. Hussakof[27] compared *Pe. arctata* with Fristch's genus *Sphaerolepis*. He concluded that *Peplorhina* and *Sphaerolepis* were synonymous and that *Sphaerolepis* should be retained in spite of the fact that *Peplorhina* had priority because *Peplorhina* was an insufficiently described genus. If his determination of synonymy is correct, as it would seem to be on the somewhat inadequate basis of Cope's specimen, his procedure appears the best to follow. The name ?*Sphaerolepis arctata* is used in the revised faunal list in this paper with the reservation that the generic identity of Cope's specimen has not been positively established.

20 *Ibid.*, p. 157.

21 Pp. 8–12 of ftn. 5 (1901).

22 *Catalogue of the Fossil Fishes in the British Museum*, Part II (1891), pp. 261–62.

23 Pp. 706–10 of ftn. 3 (1934).

24 P. 54 of ftn. 7 (1877).

25 "Third Contribution to the History of Vertebrata of the Permian Formation of Texas," *Proc. Amer. Phil. Soc.*, Vol. XX (1882), pp. 394–95.

26 Pp. 12–13 of ftn. 5 (1901).

27 Pp. 170–71 of ftn. 9 (1911).

Cope[28,29] named two species of the amphibian *Cricotus*. There is no adequate basis for differentiating the two. They occur in the same deposit, are similar in size, and were called distinct species primarily because the remains were from different parts of the skeleton. In the revised faunal list all remains of *Cricotus* from the Oakwood locality are referred to the first-named species, *Cr. heteroclitus* Cope.

The genotype of *Diplocaulus*, a genus now much better known from the Texas Permian, came from the Oakwood locality. The genus was based upon several vertebrae (W. M. 6513, 6514, 6515, 6516). Although Cope first assigned these vertebrae to the Pelycosauria, he shortly recognized their amphibian affinities. Only a single species, *Diploc. salamandroides* Cope, was named. The species is valid, but reference of specimens from other localities to it is difficult because the vertebrae lack features which are clearly diagnostic at the species level.

L. tricarinatus Cope, the only recognized species of this genus, was described from the Oakwood locality on the basis of vertebrae.[30] The multitude of specimens known from the Permian of Texas have been referred to the species. The nature of the type specimens, poorly preserved vertebrae (W. M. 6525 the holotype, and 6527, 6528, paratypes), make it uncertain that this reference is correct. Furthermore, there clearly is more than one species of *Lysorophus* from the Texas red beds although as yet specific names have not been given.[31]

A. S. Romer and L. I. Price[32] referred all the reptilian remains, designated by Cope as three species of *Clepsydrops* and one of *Archaeobolus*, to two of Cope's original species *Cl. colletii* and *Cl. vinslovi*. *Cl. colletii* includes the large forms and *Cl. vinslovi* the small ones. No important morphological differences, other than size, have been found between the two. S. W. Williston[33] described a specimen as ?*Captorhinus illinoisensis*. Romer and Price state that this specimen shows no difference from *Cl. vinslovi* and that it is to be referred to that genus and species. No cotylosaurs are known from this deposit, the only reptile being *Clepsydrops*, a primitive pelycosaur which is unknown from any other locality.

On the basis of the revisions cited above, the faunal list of the Oakwood locality is as follows:

Class Chondrichthyes
- Subclass Elasmobranchii
  - Order Xenacanthodii
    - Family Xenacanthidae
      - *X. ?compressus* (Newberry)
      - *X. gracilis* (Newberry)
      - *X. quadriseriatus* (Cope)
- Subclass Holocephali
  - Order Bradydonti
    - Family Petalodontidae
      - *J. strigilina* Cope

Class Osteichthyes
- Subclass Choanichthyes
  - Order Dipnoi
    - Family Ctenodontidae
      - *S. paucicristatus* (Cope)
      - *S. serratus* (Cope)
- Subclass Actinopterygii
  - Superorder Chondrostei
    - Order Palaeoniscoidea
      - Family Trissolepidae
        - ?*Sp. arctata* (Cope)

Class Amphibia
- Subclass Apsidospondyli
  - Superorder Labyrinthodontia

[28] Pp. 404–11 of ftn. 6 (1875).

[29] P. 186 of ftn. 8 (1877).

[30] *Ibid.*, p. 187.

[31] E. C. Olson, "The Fauna of the *Lysorophus* Pockets in the Clear Fork Permian, Baylor County, Texas," *Jour. Geol.*, Vol. XLVII (1939), pp. 394–95.

[32] "Review of the Pelycosauria," *Geol. Soc. Amer. Spec. Papers No. 28* (1940), pp. 212–15.

[33] *American Permian Vertebrates* (Chicago: University of Chicago Press, 1911), p. 69.

Order Embolomeri
Family Eogyrinidae
Cr. heteroclitus Cope
Subclass Lepospondyli
Order Microsauria
Family Lysorophidae
L. tricarinatus Cope
Order Nectridia
Family Keraterpetonidae
Diploc. salamandroides Cope
Class Reptilia
Subclass Synapsida
Order Pelycosauria
Family Ophiacondontidae
Cl. colletii Cope
Cl. vinslovi Cope

THE FALMOUTH LOCALITY

THE DEPOSIT

The most productive channel deposit so far found in the Illinois Pennsylvanian is located in the center SW. ½, Sec. 15, T. 7 N., R. 3 E., about 3½ miles southeast of Falmouth, in Jasper County. This locality was called to the writer's attention by Professor J. Marvin Weller of the Department of Geology, the University of Chicago. A moderately large collection of vertebrate specimens has been obtained in the course of three visits to it.

The beds are exposed in an abandoned road-cut. The total thickness of the vertebrate-bearing deposit is about two feet. It lies on an irregularly eroded, massive marine limestone and is overlaid by an unfossiliferous gray shale. The channel lies high in the Illinois Pennsylvanian, but its precise age has not been determined.

The channel appears to have trended east-west at right angles to the direction of the road. Quarrying operations followed the deposit from its northern limit, south for about 15 feet, at which place the beds pinched out. The lower part of the deposit is composed of a thin-bedded sandstone with shaly partings and the basal three or four inches are composed of sandy shale. In places throughout the lower part of the deposit are lenses of clay pebble conglomerate similar to those found at the Salt Fork locality (see p. 296).

Remains of vertebrates and invertebrates occur throughout the deposit, but the greatest concentrations are in the shaly partings between the sandstone and conglomeratic slabs. The bones and teeth are scattered, and there is little or no association of skeletal parts. As a result, most specimens are fragmentary. The bones are oriented with their long axes in the horizontal plane, parallel to the bedding, but there is no alignment indicating current direction. Invertebrates, all microscopic in size, are found throughout the deposit, but they occur in high concentration in small lenses. Bones and invertebrates are found intermixed. Some layers are composed almost exclusively of ostracodes, worm tubes, and small flakes of bone.

THE FAUNA

The following vertebrates have been identified from the Falmouth locality:

Class Chondrichthyes
Subclass Elasmobranchii
Order Cladoselachii
Family Ctenacanthidae
Ctenacanthus cf. *marshi* Newberry
Order Xenacanthodii
Family Xenacanthidae
X. cf. *latus* (Newberry)
X. gracilis (Newberry)
Class Osteichthyes
Subclass Choanichthyes
Order Dipnoi
Family Ctenodontidae
Sagenodus sp.
Family Ceratodontidae
Pr. cf. *carlinsvillensis* Romer and Smith
Class Amphibia
Subclass Apsidospondyli
Superorder Labyrinthodontia

Order Rhachitomi
Family Eryopidae
Genus indeterminate
Subclass Lepospondyli
Order Microsauria
?Family Gymnarthridae
Genus indeterminate

Description of the vertebrates.—Identification of many of the specimens has been made difficult by their fragmentary nature. For this reason, a rather detailed description of the specimens identified in the faunal list as well as a few other specimens whose affinities are uncertain are given in the following paragraphs.

Ctenacanthus cf. *marshi* Newberry

One specimen consisting of an excellently preserved lower part of a fin spine and one poorly preserved partial fin spine are tentatively referred to this species. The specimens show no differences from the type of *Ct. marshi* figured by J. S. Newberry,[34] but the characters are such that it is difficult to be certain of specific identity. *Ctenacanthus* spines occur in typical marine rocks of Devonian and Mississippian age and there are numerous marine occurrences in the Pennsylvanian. There are, however, various reports which suggest that *Ctenacanthus* also may have lived under nonmarine conditions during the late Carboniferous and the Permian. Various spines have been reported from the "coal measures." It is not indicated in these reports whether the specimens came from marine or nonmarine phases of these beds, but the implication in some instances is that they are nonmarine. A specimen has been reported from the Permian of Texas (see Hussakof). This is presumably from the red beds. The specimens from the Falmouth locality came from beds which appear to be nonmarine, judging from the associated vertebrates. There is, of course, no conclusive evidence that they were not carried in from a site of earlier deposition, but they are little worn and give no indication that they were deposited in another type of matrix. The preservation is precisely that characteristic of all bones in the deposit, and the interstices of the bone are filled with fine material of the matrix in which it was found. The implication that the specimens represent a case of primary deposition is very strong. If this is the case, they give additional evidence that *Ctenacanthus* had both a fresh and salt-water habitat during the late Carboniferous.

Xenacanthus cf. *latus* (Newberry)
(Fig. 1, *D*)

Numerous teeth and fragments of calcified cartilage represent this species in the collection. The teeth correspond closely in all respects to the type of the species described by J. S. Newberry.[35] They are large, with broad, divergent spines. The central tubercle is either small or absent. As would be expected, there is considerable size range in the specimens. Some of the smaller ones more nearly resemble *X. gracilis* (Newberry), and there is some indication that these two "species" may intergrade. Associated with some of the large teeth and scattered through the sandstone are fragments of calcified cartilage which appear to pertain in part to this species on the basis of their size and proximity to the teeth. No details of structure are shown by the cartilage.

Xenacanthus gracilis (Newberry)
(Fig. 1, *C*)

Many small teeth have been referred to this species. The base of the teeth is

[34] *Geol. Surv. Ohio*, Vol. I, Part II (1873), pp. 326–28, Pl. 35.

[35] *Ibid.*, p. 326.

small and the lateral denticles are long, divergent toward the points, and not compressed. The central denticle is moderately developed. Differentiation of this species from *X. compressus* is based on slight differences of shape and crenulation of the lateral denticles. It is entirely possible that the two are not distinct. The reference of the Falmouth specimens to *X. gracilis* is based on the lack of compression of the denticles and their lack of serration.

Order Dipnoi: Remains of lungfish constitute the major part of the fossils found in the deposit. They consist of three moderately well-preserved tooth plates, an abundance of skull plates and scales, and many ribs which are tentatively assigned to this group. The only parts upon which diagnosis can be based are the teeth. The skull bones are separated and none are diagnostic.

Proceratodus cf. *carlinsvillensis* Romer and Smith

(Fig. 1, *A*)

Two large tooth plates (W. M. 1799, 1800) appear to pertain to the genus *Proceratodus* erected by Romer and Smith[36] to receive *Ceratodus*-like Paleozoic dipnoans. In neither tooth is the inner margin clearly seen, so that comparisons of this critical area are impossible. The best-preserved tooth plate is W. M. 1799. It is a pterygoid plate which has many features in common with the holotype of *Pr. carlinsvillensis*. The specimen measures 50 mm. in length and is set with heavy ridges with a very slight tuberculation on the second ridge only. In the presence of this slight tuberculation the plate differs from that of *Pr. carlinsvillensis*, upon which no tubercula-

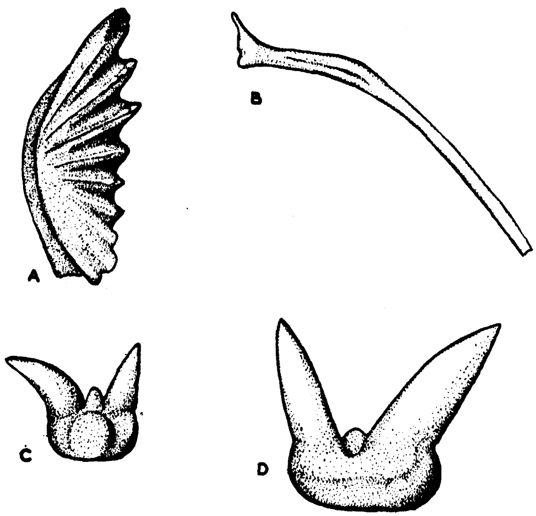

FIG. 1.—Fish remains from the Falmouth locality. *A*, Pterygoid plate of *Proceratodus* cf. *carlinsvillensis* Romer and Smith, W. M. 1799, ×¾; *B*, rib, tentatively referred to dipnoans, ×¾; *C*, inner aspect of tooth of *Xenacanthus gracilis* (Newberry), ×2; *D*, outer aspect of tooth of *Xenacanthus* cf. *latus* (Newberry), ×1.

[36] Pp. 706–10 of ftn. 3 (1934).

tion seems to be developed. There are seven strong ridges in the specimen, but, unlike the holotype of the species, there are two faint additional ridges. All the ridges differ from those of the holotype of *Pr. carlinsvillensis* in that they carry slightly farther toward the external margin of the plate. The second specimen (W. M. 1800) confirms this last observation but, unlike the first, shows no tuberculation on any ridge. It is not complete enough to allow a count of the ridges. These two specimens are close to *Pr. carlinsvillensis,* but they differ in minor respects, one of which—the number of ridges—Romer and Smith have suggested as a basis for specific differentiation. It is probable that the specimens will prove to represent a different species, but the writer feels that they cannot be considered adequate for erection of a new species until more data on the range of variation within the genus are available.

Sagenodus sp.

One tooth plate (W. M. 1801) differs markedly from the two just described in that the ridges are strongly tuberculated. It appears to be a mandibular plate. Only the outer portion of the specimen is preserved. This shows seven strong ridges, and a somewhat weathered posterior area probably accommodated three or four more. The specimen is referable to the genus *Sagenodus*, but its preservation is such that specific assignment is not possible. It resembles *S. serratus* in all features except size. It is larger than any described specimen of this species, the length being about 47 mm. It appears to be about the size of plate which might be expected in *S. ohioensis* (Newberry), but, as only the skull of this species is known, no direct comparison is possible.

It is not possible to assign the plates, scales, and ribs of the deposit to a genus among the Dipnoi. The well-preserved skull elements closely resemble those of *S. serratus*, but they are considerably larger. The most abundant vertebrate remains in the deposit are long, heavy, curved ribs (Fig. 1, *B*). They are circular in cross section in the shaft and have a rather narrow single head. Their abundance suggests that they are associated with the lungfish. They do not belong to the amphibian represented by vertebrae, since the heads are not suitable for articulation on the broad transverse processes.

Amphibia: There are numerous fragments of amphibians in the deposit but relatively few are well enough preserved to be identified. Much of the material seems to pertain either to a moderately large form assigned to the Eryopidae or to a very small form tentatively referred to the Gymnarthridae.

Family Eryopidae

A number of fragments which represent a moderately large amphibian have found scattered in the channel sand. Just enough is preserved to be intriguing. Best preserved is a spine and arch of a vertebra (W. M. 1802) (Fig. 2, *A*). Two partial spines of the same species have been found, but they add little to the details determined from the one specimen. In addition, there is a very poorly preserved fragment of a lower jaw and one of part of a pelvis. There are other fragments of bone which may belong to this amphibian, but they are so broken that no guess concerning their identity is possible. There is no assurance that these various parts belong to the same species or even the same genus, but all seem to pertain to animals of about the same size

and the same general type. It is possible that they are actually fragments of one individual.

The well-preserved vertebra is most definitive. It consists of a spine, a neural arch with two zygapophyses, and one complete transverse process. The spine, which is 37 mm. high, is topped by a quadrilateral, rugose surface. The spine has been compressed but clearly shows a roughly ridged lateral surface

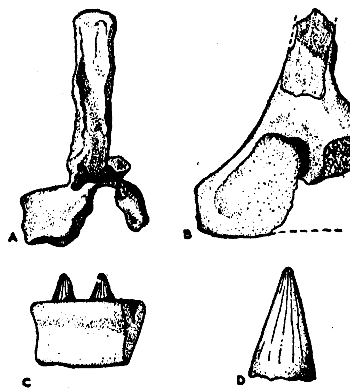

FIG. 2.—Amphibian remains from the Falmouth locality. *A*, Anterolateral aspect of vertebral spine and arch of an eryopid, W. M. 180½, ×½; *B*, partial pelvis tentatively identified as eryopid, ×½; *C*, section of lower jaw tentatively identified as eryopid, ×1; *D*, labyrinthine tooth pertaining either to Amphibia or Crossopterygia, ×½.

much like that of *Eryops*. The neural arch is narrow and the zygapophyses are strongly inflected. The transverse process is long and terminates in a single, broad facet for the rib head. In all these features the vertebra is like one of *Eryops*. It differs principally in size and proportion. No mature specimen of *Eryops* is so small as the specimen under consideration, and in none is the spine so long in proportion to the other dimensions. The vertebra, while resembling those of *Eryops*, certainly belongs to another genus, but the specimen is not adequate for a valid definition of the genus.

A fragment of lower jaw, about 50 mm. long, is another indication of a moderately large amphibian. Several teeth are visible (Fig. 2, *C*), and they alone give some indication of the relationship of the specimen, since the jaw itself is poorly preserved and cannot be satisfactorily cleared of matrix. The teeth measure about 4 mm. in height and are broad basally, measuring about 2 mm. longitudinally. They taper to a sharp point. The crowns are ridged, suggesting a highly developed labyrinthine structure. The teeth are in general *Eryops*-like but, like the vertebra, cannot be considered as pertaining to that genus. The vertebra and jaw lay about 1 foot apart in the same bed of the deposit, suggesting that they, with the pelvis which was close by, may have come from the same animal.

The partial pelvis (Fig. 2, *B*) consists of the ischium and a small part of the ilium and pubis. It is clearly that of a tetrapod and is of about the size to be anticipated in an animal with the vertebra described above. There is, however, nothing definitive to suggest that the two belong to the same species or even, for that matter, that they are to be placed in the same family.

One other specimen may be mentioned in connection with this suite of amphibian remains, a large labyrinthine tooth which must represent an animal unknown from any other fragments in the deposit (Fig. 2, *D*). The tooth is conical and measures about 31 mm. in height. It is much like the large palatal teeth of *Eryops* but is not unlike homologous teeth in certain large crossopterygians. It may belong to either the amphibians or the crossopterygians.

?Family Gymarthridae

Two small lower jaws, a fragment of a snout with five teeth, a small skull plate, and various other fragments are thought to belong to the Gymnarthridae. One of the lower jaws (W. M. 1803), which consists of part of the ramus carrying four teeth (Fig. 3, *A*), is moderately well preserved. The jaw measures 6.2 mm. in length, and the four preserved teeth form a row 4.1 mm. long. The teeth are rather bulbous, as in most gymnarthrids, but are moderately long and pointed. The highest has a crown length of 2.1 mm., and the shortest is just under 1 mm. These teeth show strong resemblances to those of the gymnarthrids and are the principal basis for assignment of the specimens to this family. Admittedly, such reference is not based on the sort of evidence which can be considered conclusive.

The teeth in the fragment of snout are very much like the corresponding teeth in *Euryodus* and many well represent a related genus (Fig. 3, *B*). Several small skull plates which are deeply sculptured may belong to the same type of animal, but in none are there definitive characters which validate this suggested relationship.

Description of the invertebrates.—Many parts of the channel deposits are rich in microscopic invertebrates. Some small pockets are composed almost exclusively of thin-shelled, simple ostracodes. Worm tubes are mixed with the ostracodes and occur scattered throughout all parts of the sandstone, clay, and conglomerate. The ostracodes all appear to belong to two genera, *Cavellina* and *Cytherella*. Specific determinations, difficult in these genera, have not been attempted. These two genera were also noted from the red horizon near La Salle, Illinois. No representatives of the genus *Bairdia* occur at Falmouth. The species of *Cavellina* and *Cytherella* from the Falmouth locality appear to be different from those identified in the red deposit. The tests are thinner and more subject to crushing. The worm tubes all appear to belong to a single species, *Spirorbis anthrocosia*, which is characteristic of the Pennsylvanian.

Discussion of the fauna.—Both the vertebrates and the invertebrates point to fresh-water origin of the Falmouth deposit. The only element suggesting marine origin in the shark *Ctenacanthus*,

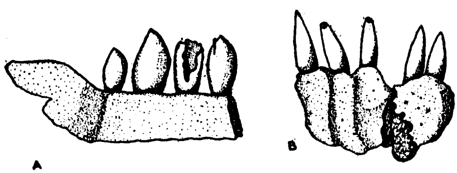

FIG. 3.—Amphibians from the Falmouth locality. *A*, Lower jaw tentatively referred to the Gymnarthridae, ×5; *B*, fragment of snout tentatively referred to Gymnarthridae, ventral aspect, ×5.

whose occurrence has been discussed earlier. The vertebrate fauna, although composed of fragmentary specimens, is of interest in showing an assemblage different from that found in typical coal-swamp deposits. The only comparable fauna in the Pennsylvanian of Illinois is that found at the Oakwood locality. Both of these faunas give evidence of a primitive, "red beds" type of fauna, which should throw some light upon the development of the better known faunas of the Dunkard, Abo, Wichita, and Clear Fork when better-preserved remains are discovered. In both localities, Falmouth and Oakwood, there are fishes which are related to the xenacanthids and dipnoans of the lower Permian. There appears to have been little change in these groups between the Pennsylvanian and the

Permian. Among the amphibians there is evidence of at least four groups well known in the Permian; the Embolomeri, in *Cricotus* of Oakwood; the Rhachitomi, in the eryopid from Falmouth; the Microsauria, in the small gymnarthrid from Falmouth; and the Lysorophia, in *Lysorophus* from Oakwood. Among the reptiles, the only known genus is *Clepsydrops*, a primitive pelycosaur, from Oakwood. It is interesting to note that no cotylosaurs have been found in the Pennsylvanian of Illinois. It seems certain that they were in existence at the time of the formation of the deposits. Their absence probably is to be accounted for merely by accident of preservation, or it may be that they lived in a somewhat different environment from that of any of the types which are preserved.

SALT FORK LOCALITY

Just south of the Salt Fork branch of the Vermilion River, along the section line between Sec. 31 and Sec. 32, T. 19 N., R. 13 W., a deep road-cut has exposed a massive, somewhat irregularly bedded, yellowish-gray sandstone about 20 feet thick. The northern end of the deposit has been destroyed by the river, but the sandstone can be followed south for 150 feet in the road-cut. The same sandstone crops out in the valley wall about 50 feet west of the highway. The sand appears to have been deposited in a channel which trended northeast by southwest, so that the road cuts it nearly at a right angle.

The stratigraphic age of this deposit, as is the case with many Pennsylvanian channels, is not entirely certain. The sandstone lies well above the Lonsdale, which is exposed near the bridge to the north of the river. Mr. George Wilson, who called the deposit to the writer's attention, suggests that it may be a La Salle equivalent.

Much of the deposit consists of a massive, thickbedded, micaceous sandstone. Near the base is a thin, fine, red-and-green layer of sand which passes laterally into a lenticular red conglomerate near the north end of the exposure. The lenticular body, which crops out on both sides of the road, and the fine sand immediately above and below it have yielded fragmentary remains of vertebrates. As in the case of the Falmouth channel, the vertebrates are associated with lenses of clay pebble conglomerate.

The remains of vertebrates obtained from this locality are all very fragmentary. The following have been identified:

Class Chondrichthyes
- *X*. cf. *latus* (Newberry)
  - 6 teeth and one spine
- *Orodus* sp.
  - 1 tooth

Class Amphibia
- 2 fragments of small limb bones and several fragments of skull plates or dermal armor

Labyrinthine teeth
- 2 specimens of small size which may pertain either to crossopterygians or amphibians

In addition to these traces of vertebrates, three brachiopods were found in close association with the vertebrate remains.

There is a clear case of mixing of marine and fresh-water species in this deposit. The conditions of origin are not entirely clear. The sandstone overlies a gray shale which appears to have been the source of the clay pebbles in the lenticular conglomerate. The marine fossils may well have been washed in from the shale or from another marine deposit. Both *Orodus* and the brachiopods are typical marine Pennsylvanian forms. They do not, however, show any evi-

dence of extensive transportation. It seems possible that the sandstone may have been developed as a shallow-water deposit under marine conditions or that it may have developed in a subaerial channel. There is little conclusive evidence for either interpretation.

MAZON CREEK AND VICINITY

The famous plant-bearing shales of Mazon Creek and the near-by strip mines have produced a considerable number of vertebrates. These have been described and discussed by many writers. Certain elements of the fauna have received close attention in recent years. The knowledge of these may be considered to be in a moderately satisfactory state. Other parts have received little attention since early studies were made. It is not the purpose of this paper to undertake detailed systematic and morphological revisions but rather to give a survey of the present knowledge of the Pennsylvanian vertebrates from Illinois. It is recognized that certain elements of the Mazon Creek fauna are in need of restudy. In the course of the following discussion, areas which are in need of reworking are indicated. It is hoped that this summary of the status of the fauna will encourage more thorough studies.

Attempts to found species on the basis of fragmentary and, in some instances, poorly preserved materials characteristic of the ironstone nodules of Mazon Creek have resulted in an unjustified multiplication of names. While a rather large number of fish specimens is known, adequately preserved amphibians probably do not number over twenty. The majority of good specimens of amphibians have been designated as holotypes. Revisions are almost certain to reduce the number of named species; this has been the case in areas where careful revisions have been made. Adequate faunal lists probably will be somewhat shorter than the one presented at the end of this section, and this list itself is considerably shorter than the earlier ones from which the faunal list which follows was prepared.

The shale bearing the fossiliferous ironstone nodules has been dated as Westphalian C–D by Darrah.[37] He suggests that they fall in G–H of Dix's system of terminology. Westoll, re-evaluating the evidence submitted by Darrah, suggests that the beds are slightly younger and should be placed in floral zone H. These correlations are based entirely on paleobotanical evidence, for the vertebrates and invertebrates have not as yet proved of value for detailed dating. Most of the vertebrates have been obtained by collectors primarily interested in the flora, and vertebrate remains are so rare that it is not feasible to collect the area solely for them.

C. R. Eastman[38,39,40] and Moodie[41] compiled faunal lists of the Mazon Creek vertebrates which will serve as bases for consideration of the fauna. The following list was drawn from these sources and shows genera and species entered in the classification in the manner of these two writers:

[37] T. S. Westoll, "The Family Hapolepidae: A New Family of Late Carboniferous Bony Fish," *Bull. Amer. Mus. Nat. Hist.*, Vol. LXXXIII (1944), p. 9.

[38] "The Carboniferous Fish Fauna of Mazon Creek, Illinois," *Jour. Geol.*, Vol. X (1902), pp. 540–41.

[39] "Some Carboniferous Cestraciont and Acanthodian Sharks," *Bull. Mus. Comp. Zoöl.*, Vol. XXXIX (1902), p. 97.

[40] "Carboniferous Fishes from the Central Western States," *Bull. Mus. Comp. Zoöl.*, Vol. XXXIX (1903), p. 194.

[41] Pp. 12–13 of ftn. 2 (1916).

Fish
Elasmobranchii
Pleuracanthus (*Diplodus*) *compressus* (Newberry)
P. (*Dip.*) *latus* (Newberry)
P. (*Dip.*) *lucasi* (Newberry)
Acanthodes beecheri Eastman
A. marshi Eastman
Campodus scitulus (St. John and Worthen)
Dipnoi
Ctenodus sp. undesc.
Sagenodus cristatus Eastman
S. foliatus Cope
S. lacovianus Cope
S. occidentalis (Newberry and Worthen)
S. quadratus (Newberry)
S. quincuniatus Cope
S. reticulatus (Newberry and Worthen)
S. textilis Hay
Crossopterygii
Rhizodopsis? mazonius Hay
Coelacanthus exiguus Eastman
Co. robustus (Newberry)
Co. elegans Newberry[42]
Actinopterygii
Eurylepis sp. indet (fide J. S. Newberry)
Rhadinichthys gracilis (Newberry and Worthen)
Elonichthys disjunctis Eastman
E. hypsilepis Hay
E. perpennatus Eastman
Platysomus circularis Newberry and Worthen
Pl. lacovianus Cope
Cheirodus orbicularis (Newberry and Worthen)
Class Amphibia
Subclass Euamphibia
Order Branchiosauria
Family Brachiosauridae
Micrcrpeton caudatum Moodie
Eumicrerpeton parvum Moodie
Mazonerpeton longicaudatum Moodie
M. costatum Moodie
Order Caudata
Suborder Proteida
Family Cocytinidae
Erierpeton branchialis Moodie
Subclass Lepospondyli
Order Microsauria
Family Amphibamidae
Amphibamus grandiceps Cope
Am. thoracatus Moodie
Cephalerpeton ventriarmatum Moodie
Family Molgophidae
Erpetobrachium mazonensis Moodie
Subclass Stegocephalia
Order Temnospondyli
Suborder Embolomeri
Family Cricotidae
Spondylerpeton spinatum Moodie

Revisions in recent years have modified the concepts of the dipnoans and of *Eurylepis* and *Rhadinichthys* among the fish and of most of the amphibians. Careful study of the other fishes is needed. The problems of the placoderms and the sharks are not serious and probably could be readily resolved. A review of the crossopterygians and the majority of actinopterygians will necessitate study of all the scattered specimens and a careful analysis which takes cognizance of recent developments in taxonomy. This will be a long and difficult task.

Even a cursory study of certain groups indicates taxonomic changes which are desirable. *Pleuracanthus* should be replaced by *Xenacanthus*. That there are three species of this genus is uncertain, but, since the determination of species based on single teeth in this genus is difficult if not impossible, the three may be retained until an adequate basis for differentiation is developed. *Acanthodes* should be replaced by *Acanthoessus*, which has priority.[43] There are two species of the genus present, but that

[42] This species is not entered in any of Eastman's lists but is suggested as being present in several papers; see, for example, "Fossil Fishes in the Collection of the United States National Museum," *Proc. U.S. Nat. Mus.*, Vol. LII (1917), p. 271.

[43] O. P. Hay, p. 542 of ftn. 15 (1929).

they are actually distinct from species named from other areas is by no means certain. *Acanthoessus* should be classified as a placoderm (or aphetohyoidean) rather than as an elasmobranch. *Ca. scitulus* is an edestid fish whose specific designation is uncertain.

The dipnoans have been restudied by Romer and Smith.[44] Since all but one species, *S. cristatus*, were established on the basis of scales and the variation of scales from the nodules is no greater than that in a single living species of lungfish, these writers have referred all such specimens to the first-named species, *S. occidentalis*. They imply that this may not be the true answer to the problem of specific identity, since dipnoan scales are of little or no diagnostic value at the specific level. It appears to be the best solution possible in view of the nature of the material. They refer *S. cristatus* to the genus *Ctenodus* but do not consider the specific relationships of the single tooth plate which is the basis for the species. The species is probably indeterminate, since the preservation of the plate is poor. In recognition of the indeterminate nature of the specimen, it is entered in the faunal list of the present paper as *Ctenodus* sp. Whether this is the same specimen as the undescribed specimen of *Ctenodus* in Eastman's faunal lists or not seems in doubt. In Eastman's first list,[45] *Ctenodus* sp. undesc. is entered, and in the second *S. cristatus* appears in addition. But there is no description of *Ctenodus* by Eastman or by any later writer, and there is good reason to suppose that there is actually only one lungfish tooth from Mazon Creek which has been recorded in the literature.

Only one species of crossopterygian has been described from adequate material, *Co. exiguus* Eastman. *Rhizodopsis?* and *Co. robustus* were described from inadequate fragments. *Co. elegans* was first suggested as being present in a statement by Newberry to the effect that he had received a species of *Coelacanthus* which did not appear to be different from the Linton, Ohio, *Coelacanthus*. Eastman referred several specimens to this species tentatively but was indefinite about their true position. It seems apparent from the available figures that *Co. exiguus* is distinct from the Linton species and that all the other specimens are not far from *Co. exiguus*. More study of the actual specimens is necessary to clarify the situation. For the present, it seems best to refer all specimens of the genus to the one well-defined species, *Co. exiguus*.

Four species of *Elonichthys* have been described. There is a rather large number of species of the small fish known, and restudy of these probably would result in a reduction of the number of species. The differences between the species as described are slight and may be caused by such factors as the degree of maturity and the orientation of specimens designated as holotypes. Until such a study is made, the four species recorded at Mazon Creek should be retained since they are adequately described from determinable specimens.

Platysomus and *Cheirodus* are distinct genera as indicated by the figures by Eastman.[46] That there are two species of *Platysomus* seems doubtful, and a restudy of the materials should be made.

Westoll[47] has restudied certain of the actinopterygian fish and indicated their position in his Family Halpolepidae. He gives a concise summary of the work on

[44] Pp. 702–4 of ftn. 3 (1934).

[45] P. 541 of ftn. 38 (1902).

[46] Pp. 5 of ftn. 40 (1903).

[47] P. 10 of ftn. 37 (1944).

these forms as follows [footnoting altered to conform to practices of *Journal of Geology*].

"Newberry and Worthen[48] described a small fish from this locality as *Palaeoniscus gracilis* Newberry and Worthen. Later Newberry[49] noted the presence of a specimen of *Eurylepis* 'probably not distinct from those found at Linton.' Hay[50] and Eastman[51,52,53] referred *Palaeoniscus gracilis* Newberry and Worthen to the genus *Rhadinichthys*. Later, Eastman[54] described and figured a specimen of *Rh. gracilis* which was later discussed by [L. S.] Berg[55] who referred it to a new genus and species, *Teleopterina improvisa* Berg, the type of a new family. Westoll[56] stated that *Teleopterina* is a synonym for *Pyritocephalus* Fritsch."

The following actinopterygian fish were listed by Westoll in this revision: *Haplolepis* cf. *tuberculata* (Newberry), *H.* cf. *ovoidea* (Newberry), *Pyritocephalus gracilis* (Newberry and Worthen), and *Py. comptus* Westoll.

This revision offers a valid and simple resolution of the difficulties which have plagued this suite of specimens. It is indicative of the sort of revision which is desirable for other actinopterygians and of the sort of solution which might come from such work.

For all cases in which there is serious doubt concerning the validity of species among the fish, the practice, in compiling the faunal list at the end of this section, has been to retain well-described species, pending work which will clarify their status. This almost certainly does not give an accurate representation of the fauna, but it does not, on the other hand, eliminate species which may be valid. The placing of the genera is sufficiently accurate that the all-over aspect of the fauna is well portrayed in the list. For the purposes of the present paper, this accomplishes what is desired—establishment of an adequate basis for general comparisons of the vertebrate localities in the Pennsylvanian of Illinois.

Moodie[57] made a comprehensive report on the amphibians, in which the faunal list given on page 298 of this report was included. Since the publication of his report there have been extensive and fundamental changes in the concepts of classification of the Amphibia. A. S. Romer[58] indicated that not only the four species of amphibians described by Moodie as branchiosaurs but a number of others, including *Amphibamus*, belong in this group. The same writer[59] gave convincing evidence that many branchiosaurs are in reality larval labryinthodonts. This certainly seems to apply to the majority of Mazon Creek specimens, which are clearly im-

48 "Descriptions of Fossil Vertebrates," *Geol. Surv. Ill.*, Vol. IV (1870), p. 347.

49 "Paleozoic Fishes of North America," *Monogr. U.S. Geol. Surv. No. 16* (1889), pp. 212, 214–25.

50 "Bibliography and Catalogue of the Fossil Vertebrata of North America," *Bull. U.S. Geol. Surv.*, Vol. CLXXIX (1902), pp. 1–868.

51 Pp. 55–99 of ftn. 39 (1902).

52 Pp. 535–41 of ftn. 38 (1902).

53 Pp. 163–226 of ftn. 40 (1903).

54 Ftn. 42 (1917).

55 "*Teleopterina*, n.g. a highly organized actinopterygian from the Carboniferous of North America," *Compt. Rend.* (Doklady) *Acad. Sci. U.R.S.S.*, Vol. IV (1936), pp. 345–47.

56 "The Distribution of Certain Specialized Carboniferous Bony Fishes," *Rept., Ann. Meeting Brit. Assoc. Adv. Sci.* (108th yr.; Cambridge, 1938), Sec. C (Geol.), p. 425.

57 Pp. 3–222 of ftn. 2 (1916).

58 "The Pennsylvanian Tetrapods of Linton, Ohio," *Bull. Amer. Mus. Nat. Hist.*, Vol. LIX (1930), pp. 77–147.

59 "Notes on the Branchiosaurs," *Amer. Jour. Sci.*, Vol. CCXXXVII (1939), pp. 748–61.

mature. D. M. S. Watson[60] recognized the great similarity of the more mature branchiosaur skulls, such as that of *Branchiosaurus amblystomus* Credner of Europe, and the labyrinthodonts, and indicated that the branchiosaurs may have come from the embolomeres. Regardless of the interpretation, it seems clear that the branchiosaurs have affinities with the labyrinthodonts and that most of the amphibians from Mazon Creek are actually larval labyrinthodonts. *Micrerpeton*, *Eumicrerpeton*, and *Mazonerpeton* certainly fall in this category. The position of *Erp. mazonensis* is less certain. It consists of a scapula, clavicle, humerus, radius, and possible rib. These bones differ from comparable elements in most branchiosaurs only in the slightly higher degree of ossification of the articular surfaces of the limb bones. Tentative assignment to the branchiosaur assemblage seems to be the best disposition of the genus. *Am. thoracatus*, named from a rather poor specimen, is not closely related to *Am. grandiceps*. Its reference to the genus *Amphibamus* gives a false impression of its affinities, but the specimen is hardly adequate to be the type of a new genus. It is tentatively assigned to the branchiosaurs, and, in order to preserve its identity in the faunal list, it is entered as "*Amphibamus*" *thoracatus*.

Watson re-examined the type of *Am. grandiceps* and a specimen tentatively assigned to that genus by Romer to reach a somewhat different conclusion from that of Romer, who had suggested that the genus belonged to the branchiosaurs. He found that *Am. grandiceps* and the second specimen, which he named *Miobatrachis romeri*, showed marked divergence from the branchiosaurs and that they had progressed in the direction of the primitive anuran, *Protobratrachus*, from the Triassic. These two genera do not belong among the branchiosaurs and and not larval labyrinthodonts. Rather, they are referred to the Family Miobatrachidae, which appears to have given rise to the frogs. Watson suggests retention of the Order Phyllospondyli to include a series of families which he thinks were derived from the labyrinthodont amphibians but which had diverged far enough from the embolomeri to deserve separate ordinal designation. The writer finds himself more in sympathy with the position of Romer, who, in his most recent classification,[61] includes the forms in question either under the Order Embolomeri or, in the case of *Amphibamus* and *Miobatrachis*, under the Order Eoanura in the Superorder Salientia. This treatment appears to express the relationships clearly and to eliminate the use of the term Phyllospondyli, which, if retained, is almost certain to cause confusion beyond any gain in clarity which it may afford.

The conclusion that the Mazon Creek branchiosaurs are larval labyrinthodonts poses a problem of nomenclature, since the mature equivalents are either unknown or not certainly identified with their larval stages at the present time. The practice of referring to the specimens by the names given by Moodie probably will persist until such time as it becomes evident that the names are in synonymy. It is quite possible that the names applied to the larval stages will have priority over the names which have been or will be given to their mature counterparts. For the present, the genera and species considered to be larval labyrinthodonts are entered in the faunal

[60] "The Origin of Frogs," *Trans. Roy. Soc. Edinburgh*, Vol. LX, Part VII (1939–40), pp. 195–231.

[61] *Vertebrate Paleontology* (2d ed.; Chicago: University of Chicago Press, 1945), pp. 590–91.

list under the names applied by Moodie with the understanding that they may prove invalid as relationships are better understood.

In addition to the branchiosaurs and miobatrachids, the fauna contain a poor impression of an amphibian named *Er. branchialis*, an embolomere based on a series of vertebrae, *Spo. spinatum*, and *Ce. ventriarmatum*, which appears to be a microsaur of uncertain family affinities. That a specimen so poor as the type of *Er. branchialis* should have been made the basis for a new genus and species is unfortunate. Reference to the lysorophids was based on very scant evidence, and there can be no real basis for thinking that this group is represented at Mazon Creek by any of the specimens now known. *Erierpeton* is dropped from the faunal list as being indeterminate.

On the basis of the revisions of certain elements of the fauna of Mazon Creek and the suggestions on nomenclature in the less well-studied groups made in the above paragraphs, the revised faunal list from this locality is as follows:

Class Placodermi
- Order Acanthodii
  - Family Acanthodidae
    - *Acanthoessus beecheri* (Eastman)
    - *Ac.* marshi (Eastman)

Class Chondrichthyes
- Subclass Elasmobranchii
  - Order Selachii
    - Suborder Hybodontoidea
      - Family Edestidae
        - *Ca. scitulus* (St. John and Worthen)
  - Order Xenacanthodii
    - Family Xenacanthidae
      - *X. compressus* (Newberry)
      - *X. latus* (Newberry)
      - *X. lucasi* (Newberry)

Class Osteichthyes
- Subclass Actinopterygii
  - Superorder Chondrostei
    - Order Palaeoniscoidea
      - Family Haplolepidae
        - *H.* cf. *tuberculata* (Newberry)
        - *H.* cf. *ovoidea* (Newberry)
        - *Py. gracilis* (Newberry and Worthen)
        - *Py. comptus* Westoll
      - Family Elonichthidae
        - *E. disjunctis* Eastman
        - *E. hypsilepis* Hay
        - *E. peltigerus* Eastman
        - *E. perpennatus* Eastman
      - Family Platysomidae
        - *Pl. circularis* Newberry and Worthen
        - *Pl. lacovianus* Cope
        - *Cheirodus* [*Amphicentrum*] *orbicularis* (Newberry and Worthen)
- Subclass Choanichthys
  - Order Dipnoi
    - Family Ctenodontidae
      - *Ctenodus* sp.
      - *S. occidentalis* (Newberry and Worthen)
  - Order Coelacanthini
    - *Co. exiguus* Eastman

Class Amphibia
- Subclass Aspidospondyli
  - Superorder Labyrinthdontia
    - Order Embolomeri
      - Family Eogyrinidae
        - *Spo. mazonensis* Moodie
    - Inc. Sed.
      - Branchiosaurs
        - *Erp. mazonensis* Moodie
        - *Eum. parvum* Moodie
        - *M. costatum* Moodie
        - *M. longicaudatum* Moodie
        - *Mi. caudatum* Moodie
        - "*Amphibamus*" *thoracatus* Moodie
  - Superorder Salientia
    - Order Eoanura
      - Family Miobatrachidae
        - *Mio. romeri* Watson
        - *Am. grandiceps* Cope
- Subclass Lepospondyli
  - Order Microsauria
    - Inc. Sed.
      - *Ce. ventriarmatum* Moodie

PIASA CREEK LOCALITY

Just below the Piasa limestone at the falls of Piasa Creek, NE. $\frac{1}{4}$, T. 8 N., R. 10 W., in Jersey County, Illinois, occurs a gray shale with phosphatic nodules containing a variety of organic remains. As

yet no vertebrates of taxonomic or morphological significance have been obtained from this deposit, for the known specimens are fragmentary, but the conditions of deposition and the faunal association are of considerable interest.

The shale, which is several feet thick, lies directly beneath the marine Piasa limestone. Above the limestone are additional shales, gray to green in color. These grade upward into red shales. The layer of red shale is about five feet thick and exposed for a distance of about 100 feet. No fossils have been found in the shales which overlie the limestone. The principal interest is in the sequence of beds, which is the same as that at several other places in the state, i.e., gray shale, limestone, gray-green shale, and red shale.

Vertebrates, invertebrates, and plants occur in the shale beneath the Piasa limestone. The vertebrates and invertebrates are in phosphatic nodules, but the plant remains, while encountered in a few nodules, are for the most part represented by fragments of fossil wood ranging from less than an inch to several inches in length and scattered at random throughout the shale. The vertebrates consist of teeth, scales, spines, small complete bones, and larger bone fragments. The specimens represented in some fifty nodules which have been studied are as follows:

Class Chondrichthyes
- *Petrodus*—10 ossicles
- *Lystracanthus*—5 spines
- *Edestus*—1 tooth
- *Orodus*—2 teeth
- A number of indeterminate fish spines, possibly shark

Class Osteichthyes
- Rhipidistians
  - Several proximal fin elements, dorsal fin supports, and scales. Genera indeterminate

The fragmentary condition of the specimens makes specific determination impossible in a number of cases and sufficiently uncertain in all that no reference of the specimens to species has been made. Most abundant are the remains of *Petrodus* and *Lystracanthus*. Here, as elsewhere, the associations are such as to suggest that these may have come from the same type of animal. The rhipidistian bones, although well preserved, do not compare precisely with those described in the few genera in which the fin structure is well known. The bones are not, however, suitable to be used as the basis for a new genus. No identifiable remains of tetrapods have been found. The fragments of large, massive bones may well be tetrapod, but all are so water-worn that their identification is impossible. They appear to have been transported far from their source.

Orbiculoidea cf. *missouriensis* is the only invertebrate which has been found. Specimens in many of the phosphatic nodules are excellently preserved. Plant remains consist entirely of fragments. While water-worn, they show considerable structure. They have not been identified, although this might be possible, but there can be no doubt that they were derived from terrestrial plants and have been carried some distance from their place of growth.

The fossiliferous shales seem to have been laid down during the early stages of transgression of marine waters over the land during the cycle of which the Piasa limestone was deposited. *Orbiculoidea* is not a typical marine brachiopod, nor does it occur in fresh-water deposits. It seems to indicate somewhat unusual conditions of deposition, perhaps brackish water. Associated with it in this shale are *Petrodus*, *Edestus*, and *Lystracanthus*. This association is char-

acteristic of the black, fissile shales of the coal measures but occurs at the Piasa Creek locality in a very different matrix. No conodonts have been found, but it is possible that they might be revealed by an analysis of the shale for microfossils. The rhipidistian bones are well preserved and do not show the water-wear characteristically exhibited by the wood and fragments of larger bones. They do not appear to have undergone any notable transportation. From these indications it would appear that this shale was deposited under brackish-water conditions, perhaps in an estuary, and that the sharks and rhipidistians were in existence in the waters at the site of the deposit. They may give evidence of the initial migration of the choanichthys into salt waters, a step fully accomplished by the coelacanths in the Permian. The shale was followed by a limestone deposited under strictly marine conditions. No vertebrates, plants, or *Orbiculoidea* occur in the limestone.

MARION COUNTY LOCALITY

A specimen of *Xenacanthus* was obtained from a plant-bearing gray shale along the course of a creek in the SW. $\frac{1}{4}$, NW. $\frac{1}{4}$, Sec. 30, T. 4 N., R. 4 E. in Marion County, Illinois, by Prof. J. Marvin Weller. This specimen (W. M. 1904) was turned over to the writer for study. It consists of twenty teeth and well-preserved parts of the calcified chondrocranium and jaws. The remains all seem to be parts of one individual. The teeth resemble those of *X. latus* (Newberry) closely, although the central denticle is rather fully developed on the smaller teeth. The shark appears to have been an isolated specimen. This type of occurrence in nonmarine beds, as the gray shale appears to be, may be encountered occasionally, but it is apparently futile to explore such shales in an effort to find vertebrates, since their occurrence is very uncommon. Several similar occurrences, commonly of merely a few teeth, have been reported from a number of areas in the state.

SUMMARY AND CONCLUSIONS

Vertebrates occur in various types of beds in the Pennsylvanian of Illinois, in red-and-gray nonmarine shales, in channel sandstones, in ironstone nodules in the coal measures, in phosphatic nodules in gray shales deposited in brackish waters, in nonmarine, plant-bearing gray shales, in black fissile shales, in cannel coal, and in typical marine beds. In no instances are the specimens preserved in a condition which makes their study entirely satisfactory. The closest approach to good preservation is in the ironstone nodules and the cannel coal. The latter seem to offer the possibility of yielding excellent specimens but as yet only one has been recovered.

A study of the faunas from these different environments gives a moderately adequate knowledge of the types of fish which were developed during the Pennsylvanian. The fresh-water sharks show little difference from those of the lower Permian and do not differ greatly from their Devonian predecessors. There is evidence that the cladoselachian type of shark, represented by *Ctenacanthus*, lived in fresh water during the Pennsylvanian. Lungfish are similar to those of the lower Permian, *Sagenodus* being the principal genus. In addition, there is an ancestral *Ceratodus*-like genus, *Proceratodus*, which is unknown in the Permian. Remains of other choanichthys are rare. Best known are the small coelacanths from Mazon Creek. The only other occurrence is in the supposed brackish-water deposits of Piasa Creek from which rhipidistians

have been obtained. There is a suggestion that the crossopterygian type was undergoing transition from fresh to marine waters. The known actinopterygians are all palaeoniscids. These were fresh-water fish and are not decidedly different from their Permian descendants.

Knowledge of the tetrapods remains far from satisfactory. A rather large number of genera representing several families has been recorded, but specimens tend to be disarticulated and broken so that it is difficult to determine much concerning their morphology. The best-known specimens come from the ironstone nodules of Mazon Creek, and many of these appear to be larval labyrinthodonts. They suggest that there was a moderately diversified fauna of medium-sized amphibians, perhaps not unlike those recorded from the Dunkard, Abo, Wichita, and Clear Fork beds. Few remains of mature individuals have been found. There are fragmentary remains of embolomeres in the nodules and in the shale at Oakwood. The rhachitomi are represented only by a few scraps from the Falmouth locality. Among the most significant specimens are *Amphibamus* and *Miobatrachus*, small but mature ancestral anurans from Mazon Creek. Lepospondyls are known from vertebrae of *Lysorophus* and *Diplocaulus* from Oakwood and from fragments assigned to the Gymnarthridae from Falmouth. A microsaur of uncertain affinities has been found at Mazon Creek. Reptiles are represented only by the primitive pelycosaur, *Clepsydrops*. These tetrapods lead to the conclusion that there actually was a well-developed terrestrial fauna, but so little is known of it that we can only get the barest insight into its true relationship to descendant faunas.

There are prospects that future work in the state will reveal other localities which will enlarge the knowledge of the Pennsylvanian vertebrates of Illinois. Most hopeful are various sandstone channel deposits which have not been thoroughly investigated for vertebrate remains. It is the writer's hope to visit a number of known channels in the near future. Cannel coals also offer possibilities, but their investigation must be concurrent with mining operations, which makes present study impossible. Additional deposits of the type found at Oakwood would seem to offer little possibility of success, although it is not impossible that new localities may turn up in the course of stratigraphic work on similar beds. It is to be anticipated that new specimens of fish and amphibians will be obtained from ironstone nodules as paleobotanical work continues in the Mazon Creek area.

SUBMARINE PHOTOGRAPHY OFF THE CALIFORNIA COAST[1]

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ABSTRACT

Bottom photography with the Ewing submarine camera was employed during the war to determine the bottom character of various areas off southern California and Mexico (Fig. 1). The photographs provide information on the appearance of the sea floor on the continental shelf, on the submerged banks, and on the walls of submarine canyons. These pictures indicate the rocky nature of extensive portions of the sea bottom. An abundance of rounded boulders and cobbles is also shown, but growth of delicate organisms on these rocks implies that rolling is now slight. Ripple marks are present on sand in areas particularly exposed to waves and currents. Finally, the smoothness of most sediment surfaces is impressive, although the surfaces of muddy sediments usually have small depressions.

INTRODUCTION

One of several large contributions by Maurice Ewing to submarine geology has been his development of a practical method of taking photographs of the sea bottom. In the course of work at the University of California Division of War Research at the United States Navy Electronics Laboratory, San Diego, we had the opportunity to make use of this new device. The results of this work are not the product of a purely scientific program, but they do show what can be expected from future work having a different emphasis.

The equipment used in submarine photography is illustrated in Figure 2. An automatic re-wind camera is housed in a brass case having a glass porthole. The case is mounted on a pole, and a reflector and flash bulb are attached beneath. The camera case and flash bulb are connected by an electrical circuit, which can be tripped by a weight suspended below the pole. In operation, the instrument is attached to a cable on a suitable winch and, after being cocked, is lowered to the sea floor. Spinning because of cable twist is retarded by a small vertical sail on the camera pole and by a swivel between the pole and cable. When the weight strikes bottom a spring closes the circuit and the camera and flash bulb operate synchronously. As soon as the device has touched bottom the outgoing cable is stopped and hoisting begun. When the camera is again at the surface it is cocked and a fresh bulb inserted. More elaborate devices were tried, but without success. Even this method required some assistance from electricians and photographers. Water pressure, rough bottoms, and the chemical effect of sea water all conspire against the continuous success of the operations.

Most of the pictures were taken with black-and-white film, but a few rolls of indoor Kodachrome were used. For naval research purposes black-and-white was more practical, since it allowed immediate developing of the films to show whether results were being obtained. For future work, color photography will undoubtedly prove superior, since the colors bring out features which are not ap-

[1] This work represents one of the results of research carried out by the University of California Division of War Research under contracts with the Office of Scientific Research and Development, Section 6.1; with the National Defense Research Committee; and with the Bureau of Ships, Navy Department.

[2] Scripps Institution of Oceanography.

[3] University of Southern California.

parent in black-and-white films. Some research will be necessary, however, before one can obtain approximately true colors of objects as they would appear to a diver.

Photographs were taken to depths as great as 140 fathoms. In the early operations the camera was only slightly inclined from the pole, so that the reflector and weight show in the picture, as in

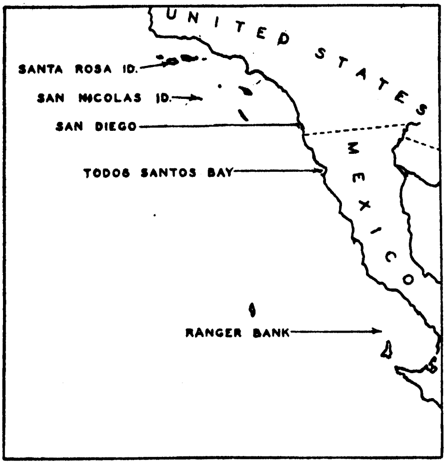

FIG. 1.—Map showing principal areas from which bottom photographs were obtained.

Figure 4. Later the case was rotated so that the photographic axis was inclined about thirty degrees from the vertical. On the average, the pictures covered about fifteen square feet, depending, of course, on the height of the camera above the bottom and on the inclination. With very clear water a much larger area can be covered by shooting from well above the bottom.

SAND AND MUD BOTTOMS

Many of the photographs are completely lacking in features of interest, particularly where detail was obscured by turbidity of the water. Some photographs of sand or mud bottoms show almost flat surfaces. The mud content of the sediment is sometimes indicated by the incipient mud cloud which is raised by the weight's hitting bottom. If the photograph were not taken almost immediately after contact, this cloud might obscure bottom. The mud surfaces usually show small depressions (Fig. 3), presumably due to burrowing organisms. The most striking feature of the sand surfaces is the number of photographs which are free from ripple marks (Fig. 4). This is true even in depths as slight as 15 fathoms. However, these areas may not always be free from ripples, since most of the pictures were taken during times of

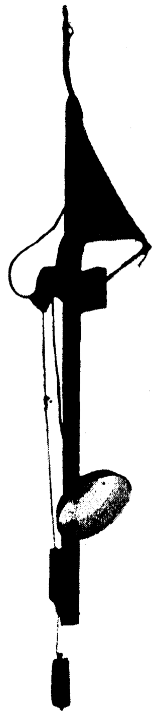

FIG. 2.—Showing the general operation of the Ewing submarine camera.

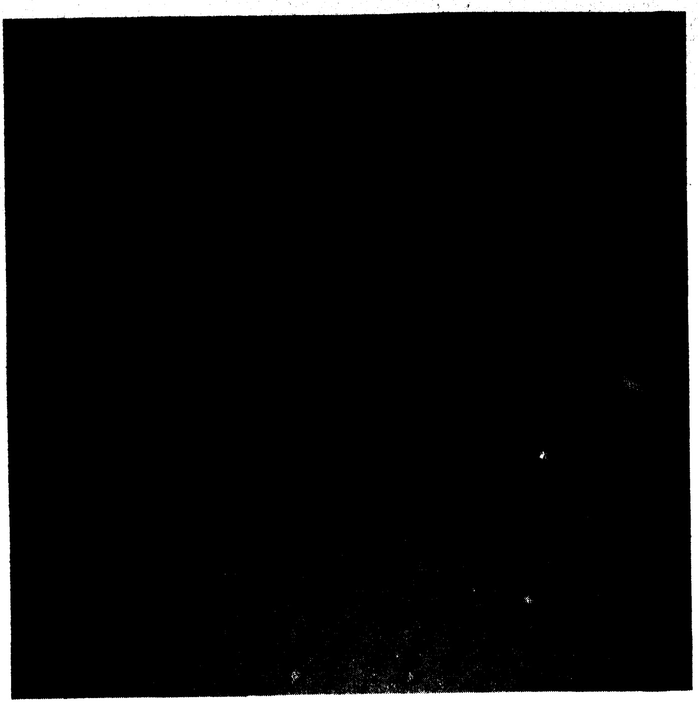

FIG. 3.—Mud, 110 fathoms, Todos Santos Bay (Lat. 31°48.2′, Long. 116°46.6′). Showing small depressions typical of muddy surfaces.

FIG. 4.—Coarse sand and shells, 14½ fathoms, San Diego area (Lat. 32°38.06′, Long. 117°14.30′)

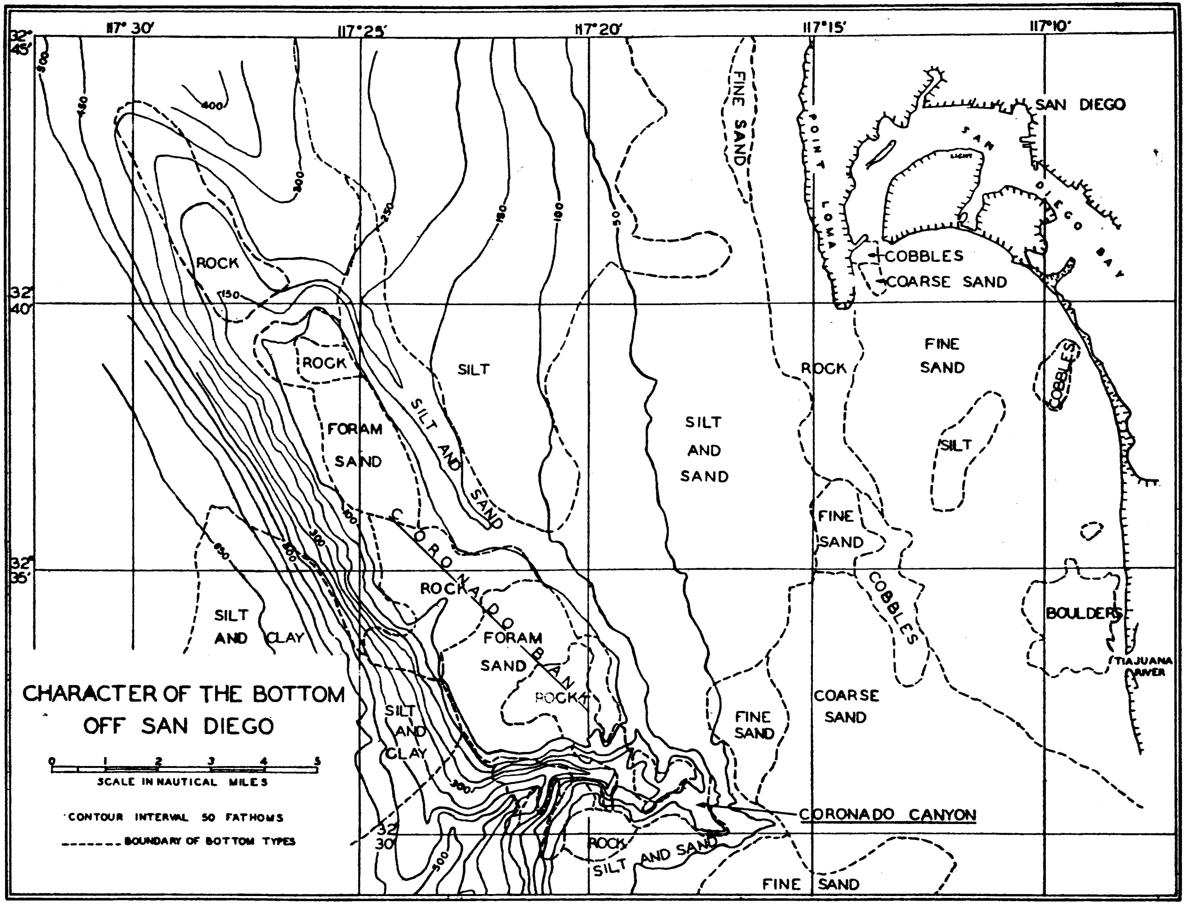

FIG. 5.—Bottom sediment chart of San Diego area

relatively smooth seas. Attempts to photograph the bottom after a rain-and-wind storm were not very successful because of high turbidity.

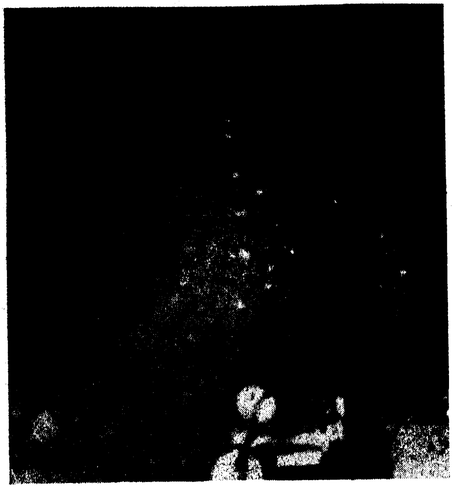

FIG. 6.—Rock, 62 fathoms, Coronado Bank (Lat. 32°32.9′, Long. 117°20.2′). Lines suggest eroded edges of tilted bedding planes.

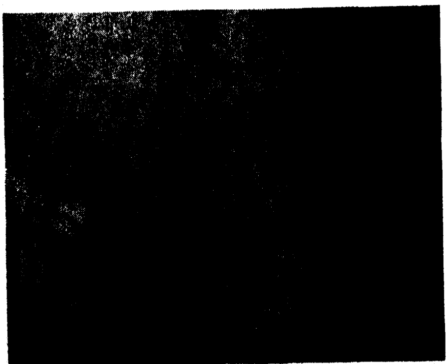

FIG. 7.—Rock, 60 fathoms, Coronado Bank (Lat. 32°33.0′, Long. 117°20.1′). Note angularity of rocks and abundance of attached marine life.

BANKS AND SHELVES

In previous work dredgings were made rather extensively on the banks and seamounts off the southern California coast.[4] Many dredge hauls recovered both angular fragments of ledge rock and rounded cobbles or pebbles. In some areas the rocks were completely buried in sediments and in others they were largely exposed as shown by the presence of incrusting organisms. Photography gives one a better idea of actual conditions on these banks than dredging. Numerous photographs were made on Coronado

FIG. 8.—Rock, 57 fathoms, Coronado Bank (Lat. 32°32.4′, Long. 117°20.4′). The photograph indicates several types of rock at various levels. Note the wrinkled mass in the upper right and the overhanging rock with a cup coral in the lower left.

Bank, which lies about ten miles southwest of San Diego (Fig. 5). Here surfaces varied from bare rock through cobbles to somewhat muddy foraminiferal sands. The rock surfaces are shown in Figures 6–10. Bedding planes in Figure 6 may indicate a tilted series of rocks. Figure 7 shows large jointed blocks of rock covered with organisms, notably brachiopods and red calcareous algae (the latter are pink in the Kodachrome transparencies). A brachiopod and a crab can be seen just above the camera trip weight. Figure 8 is perhaps the most amazing of

[4] K. O. Emery and F. P. Shepard, "Lithology of the Sea Floor off Southern California," *Bull. Geol. Soc. Am.*, Vol. 56 (1945), pp. 431–78.

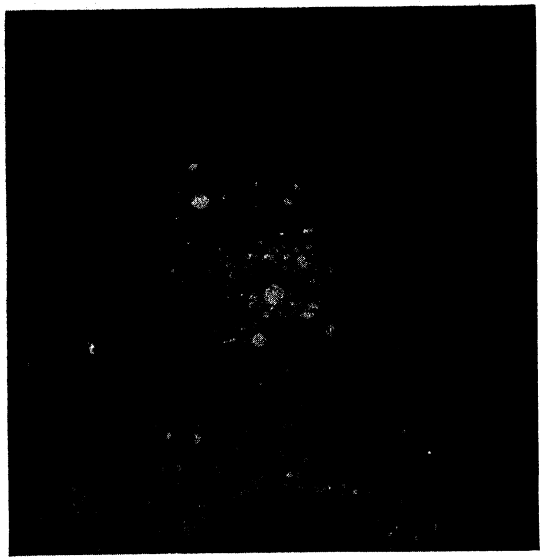

FIG. 9.—Rock and foraminiferal sand, 86 fathoms, Coronado Bank (Lat. 32°33.9′, Long. 117°23.1′). The rock resembles masses of phosphorite, such as have been dredged in abundance from this area. Many shells are present.

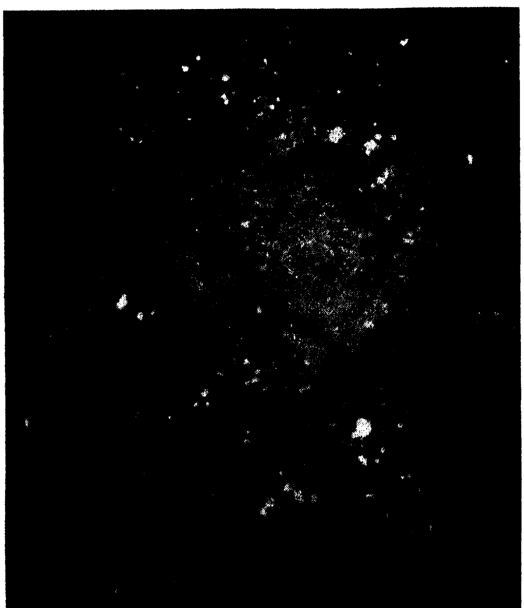

FIG. 10.—Cobbles, 67 fathoms, Coronado Bank (Lat. 32°32.5′, Long. 117°19.9′). Note the encrusting organisms on these cobbles.

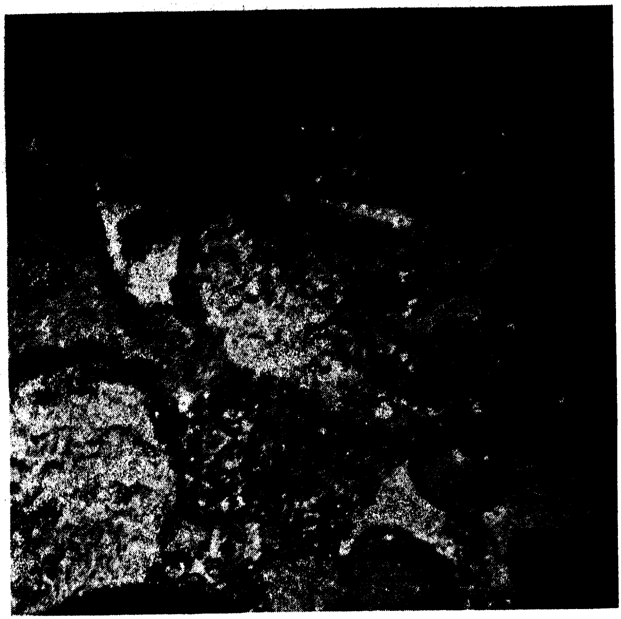

FIG. 11.—Rock and boulders, 82 fathoms, Ranger Bank (Lat. 28°31.6′, Long. 115°30.3′). A small fish (*Sebastodes*) and a sea fan (*Gorgonia*) are visible upper right.

FIG. 12.—Foraminiferal sand, 70 fathoms, Ranger Bank (Lat. 28°28.2′, Long. 115°31.5′). Note the faint ripples and the starfish.

the photographs. So far as one can tell, the surface is washed clean of sand. There appear to be several levels of rock. The lowest may be shale and the next resembles a soft limestone full of shell fragments which was dredged from this area. The wrinkled mass in the upper right may be contorted shale or perhaps some unidentified organism. Figure 8 also shows a cup coral in the lower left attached to a projecting rock mass. More photographs in this area will be taken as soon as possible.

Surfaces with cobbles and boulders are also common. Some of the mammillary surfaces, as in Figure 9, are probably phosphorite, which appears to be forming on the banks.[5] Other rocks, as in Figure 10, are rounded, presumably by rolling.

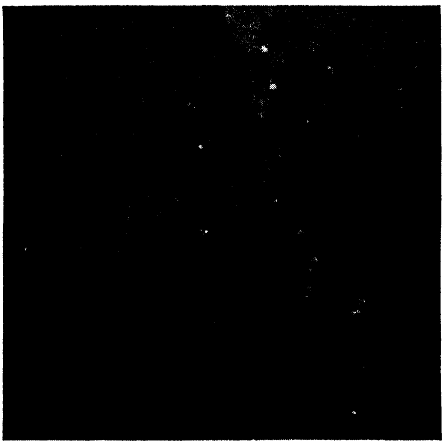

FIG. 13.—Rock and foraminiferal sand, 62 fathoms, San Nicolas Island area (Lat. 33°23.1′, Long. 119°40.9′). Tilted ledge rock and crinoids.

The incrusted surface indicates that rolling does not now occur.

Ranger Bank, off Mexico (Fig. 1), provided several good photographs because of the clearness of the water. This bank is also partly rock and partly covered with foraminiferal sand. The pictures of the rock show a group of large angular blocks and boulders (Fig. 11). Fish can be seen in each picture. The rocks are

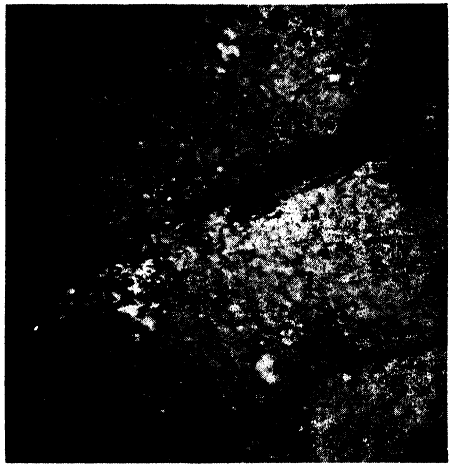

FIG. 14.—Rock, 62 fathoms, San Nicolas Island area (Lat. 33°25.1′, Long. 119°46.4′). Large pieces of ledge rock.

heavily incrusted, suggesting that here, also, there is no rolling at the present time. This was the more significant since these photographs were taken toward the end of the storm season. However, there are indications of turbulent bottom conditions, since the sand pictures show rather faint ripples (Fig. 12).

Another rocky area was found on the submerged ridge connecting Santa Rosa and San Nicholas islands (Fig. 1). Shelves less than 100 fathoms deep extend out from both islands and are separated by a saddle about 220 fathoms deep. These insular shelves correspond to banks in that they have deep water on either side. The notations on charts of this area led to the false impression that the bottom was predominantly sand-covered. Photo-

[5] R. S. Dietz, K. O. Emery, and F. P. Shepard, "Phosphorite Deposits on the Sea Floor off Southern California," *Bull. Geol. Soc. Am.*, Vol. 53(1942), pp. 815–43.

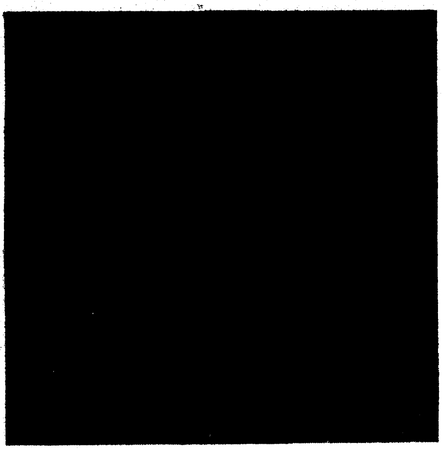

FIG. 15.—Boulders and cobbles, 85 fathoms, Santa Rosa Island area (Lat. 33°39.1′, Long. 119°57.4′). Feather crinoids (*Comatulids*) are growing on the larger rocks.

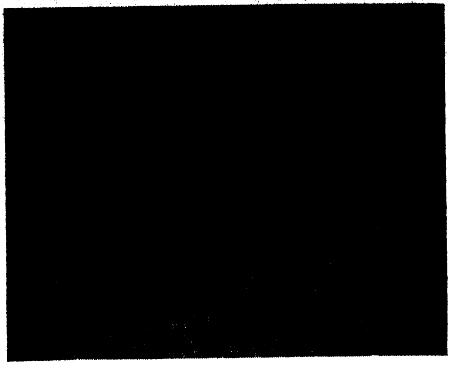

FIG. 16.—Foraminiferal sand, 55 fathoms, San Nicolas Island area (Lat. 33°21.4′, Long. 119°42.7′). Alignment of crinoids (*Comatulids*) may indicate slightly buried, tilted layers of rock.

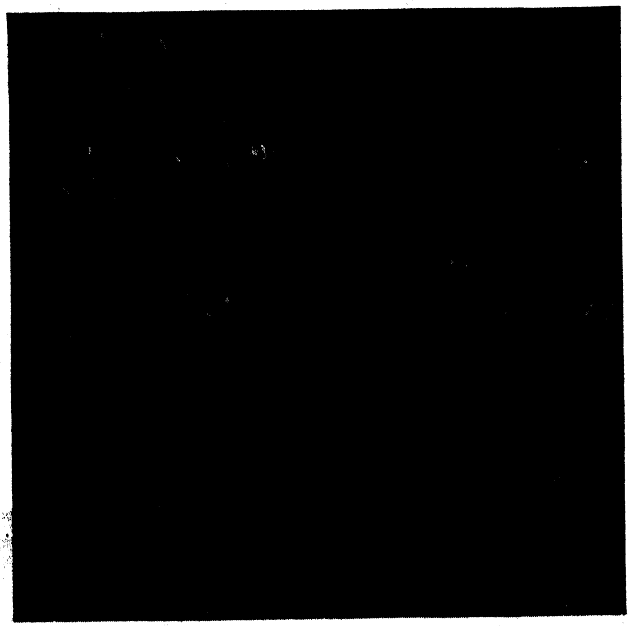

FIG. 17.—Rock and foraminiferal sand, 73 fathoms, San Nicolas Island area (Lat. 33°25.9′, Long. 119° 49.4′). The crabs (*Lopholithoides foraminatus*) appear to be all facing toward the fish in the lower center.

graphs reveal that this sand is mostly discontinuous and that rocks are predominant. It could, of course, be possible that samplers would recover only sand in such places. Figures 13 and 14 appear to show ledge rock. Apparently these rocks are consolidated sediments which have been tilted and truncated. In Figure 15 the rocks are rounded, indicating that rolling has taken place. Again, the rocks are much incrusted and feather crinoids are attached. Figure 16 shows a group of the crinoids with an apparent alignment, possibly due to the presence of a rock layer underlying a thin sand cover and affording a foothold for the crinoids. These photographs represent the first evidence of the actual habitat of these

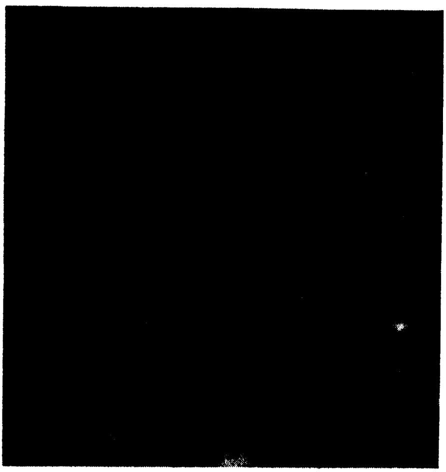

FIG. 18.—Rock and foraminiferal sand, 115 fathoms, Santa Rosa Island area (Lat. 33°47.1′, Long. 120°02.4′). Several types of sponges are shown.

deep-living organisms. In another place we found a number of crabs all pointed in the same direction and facing a fish (Fig. 17). In Figure 18 two or more types of sponges are to be seen on a rock bottom.

A few pictures of the San Nicolas–Santa Rosa Island area indicate the nature of the break in slope at the edge of the shelves. These rocks appear to preclude the possibility of extension of the insular shelf by wave-building. Figure 19 shows that the upper part of the slope

FIG. 19.—Rock, 105 fathoms, San Nicolas Island area (Lat. 33°28.2′, Long. 119°51.8′). Heavily encrusted rocks on the scarp bordering the insular shelf.

is very irregular. It is interesting that the incrustations should be pronounced at a place where the depth is over 100 fathoms. Color would be a great help in deciphering photographs of this sort. The presence of the weight and rope in these pictures suggests that the weight hit on a slope and slid a short distance down this slope before it stopped and released the spring. During the sliding the camera was moved in such a way as to bring the weight into the field of view.

Off Todos Santos Bay, lower California, there is an area of numerous small rocky banks which rise above the general level. A section made by the recording Fathometer illustrates this situation (Fig. 20). The pictures taken along the line of this section show rock bottoms on

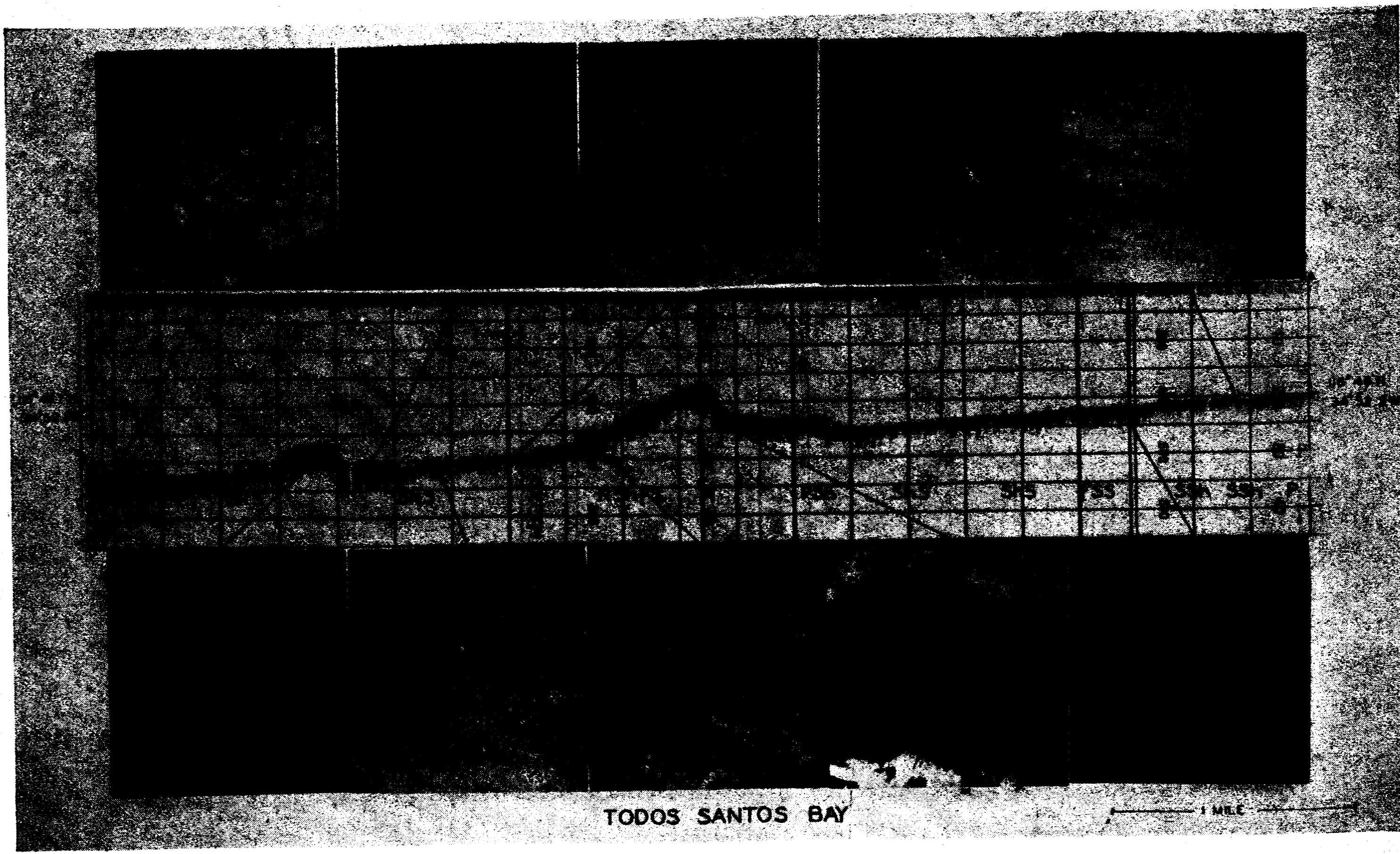

FIG. 20.—Todos Santos Bay. Relationship of bottom materials and topography as shown by a Fathometer trace. Note that the rocks are found on the high areas and the ripple-marked sands in the intervening lows.

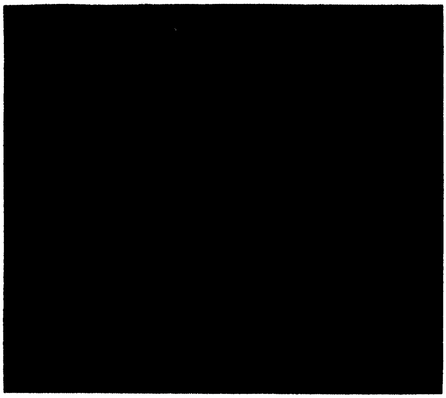

FIG. 21.—Sand, 23 fathoms, Todos Santos Bay (Lat. 31°52.4′, Long. 116°46.3′). Ripple marks having a wave length of about one-half foot.

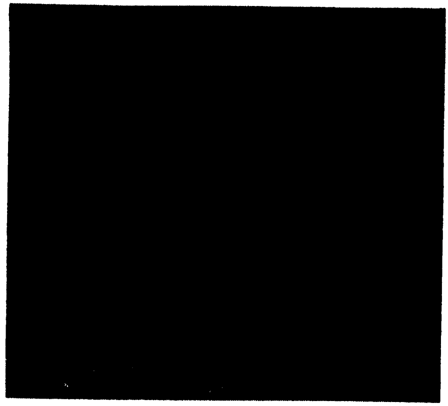

FIG. 22.—Sand, 26 fathoms, Todos Santos Bay (Lat. 32°52.56′, Long. 116°46.7′). Giant ripples with wave lengths of three feet or more. Note the shells in the trough.

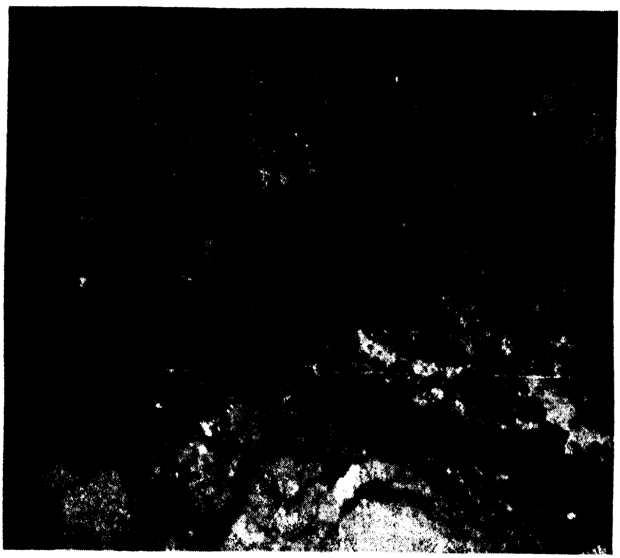

FIG. 23.—Rock and boulders, 22 fathoms, Todos Santos Bay (Lat. 31°52.6′, Long. 116°47.8′). Some type of algae is shown in the center of the picture.

the banks alternating with sand bottoms in the lower, flat areas between the banks. The sand zones are interesting, in that they all show ripples. Photographs of the ripples (Figs. 21 and 22) reveal that there are two types: one is the ordinary shallow-water ripple with about a six-inch wave length, and the other a giant ripple with a span of several feet between crests, so that only one ripple occupies the entire picture. The giant ripples may indicate strong tidal currents, since ripples elsewhere are known to exist only in areas of strong currents. It is notable that photographs of the shallower sand and silty sand areas nearer shore lack ripples. The rocky hills do not show definite outcrops, but no great doubt can be expressed that the boulder masses which are shown in Figures 23–25 represent somewhat weathered masses of ledge rock. Figures 24 and 25 show transported boulders, although their location on a hill precludes any possibility of much transportation under present conditions. Figure 26 shows a complete kelp plant, identified by Dr. E. Yale Dawson as *Isenia*, probably a new species. This picture was taken at 29 fathoms, but the kelp had probably floated from its place of growth.

FIG. 24.—Boulder, 38 fathoms, Todos Santos Bay (Lat. 31°53.6′, Long. 116°50′). This rock is three or four feet in diameter.

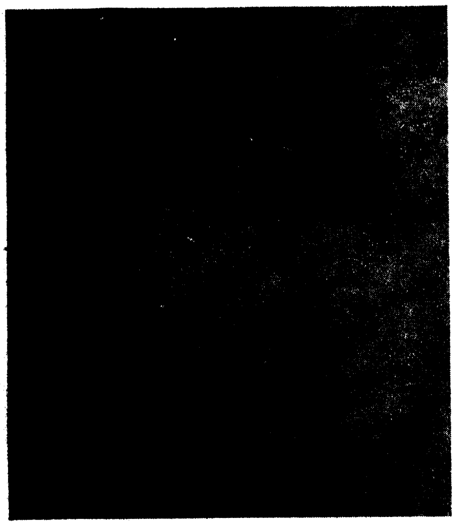

FIG. 25.—Boulders, 53 fathoms, Todos Santos Bay (Lat. 31°53.0′, Long. 116°50.4′). These rounded boulders are found near the edge of the shelf.

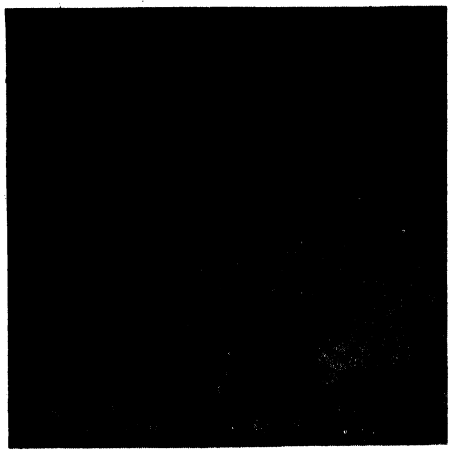

FIG. 26.—Rock, 29 fathoms, Todos Santos Bay (Lat. 31°52.5′, Long. 116°49.8′). The kelp (*Isenia*, related to *I. arborea*) probably drifted from place of growth.

FIG. 27.—Cobbles and boulders, 22 fathoms, San Diego area (Lat. 32°34.5′, Long. 117°13.2′). The growth on these rounded rocks at shallow depth is impressive.

FIG. 28.—Rock and sand, 16 fathoms, San Diego area (Lat. 32°37.2′, Long. 117°14.7′). Low-lying pink algae growing on the rocks.

RIVER COBBLES

In contrast to the boulders in the ledge-rock areas, an area south of San Diego (Fig. 5) appears to represent a true boulder-cobble bed, presumably deposited by the Tijuana River (off which it lies) at a time of greater coastal emergence. Directly off the river mouth there is a fine-sand deposit. One-half mile out, in about seven fathoms, is a boulder bed extending out another one-and-one-half miles. Beyond that is a fine-sand patch extending two miles out to a depth of about 20 fathoms. This is succeeded by a cobble-and-sand area having some interspersed boulders. This last area extends about one mile out to 24 fathoms' depth and has been traced laterally about four miles. Figure 27 was taken on this outer cobble bed. Despite much dredging, no bedrock has been found along this stretch of bottom. All the rocks recovered are rounded and bear a close resemblance to the alluvial cobbles found in many places along the coast. Growth on the cobbles indicates the absence of much rolling. However, the pictures were taken in the fall before the winter storms and after the summer period when rapid growth could be expected.

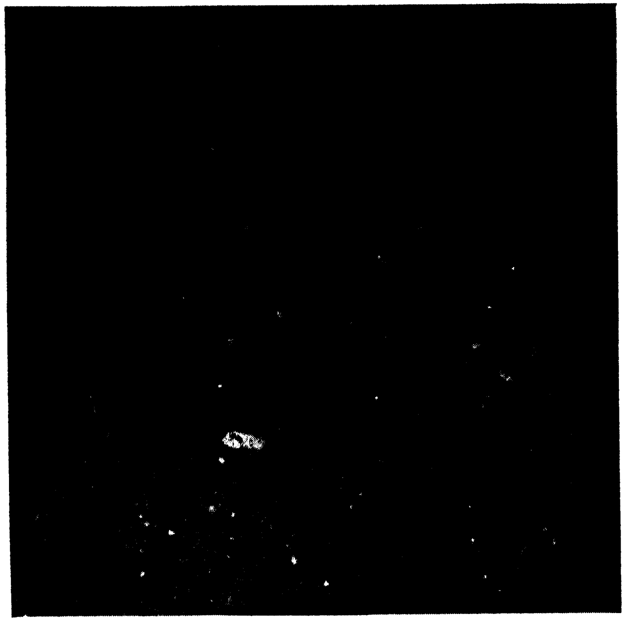

FIG. 29.—Rock, 105 fathoms, Coronado Canyon (Lat. 32°31.5′, Long. 117°20.8′). Platy layers of rock protrude on the submarine canyon wall.

North of the cobble area ledge rock is found. Photographs of the bottom in this area (Fig. 28) show small algal masses growing on the rock surface. The depth is 16 fathoms, in this case.

SUBMARINE CANYONS

The submarine canyons are a particularly fruitful field for investigation by submarine photography, and it is unfortu-

nate that the work did not allow more opportunities to photograph them. However, a few pictures were obtained of each wall of Coronado Canyon, which heads eight miles from shore off the Tijuana River (Fig. 5). It was no surprise to find that the majority of the photographs revealed the presence of rock (Figs. 29 and 30). Figure 29 shows definite outcrops, with platy slabs which project slightly in some places. Figure 30 shows a possible ravine. Those who like to think of submarine canyons as being formed by feeble mud currents flowing down muddy oceanic embankments would do well to consider the significance of these rocky walls.

ACKNOWLEDGMENTS.—Help was received from many members of the laboratory in this work. Particular mention should be made of the assistance of Mr. Albin A. Putzker and Mrs. Anne King.

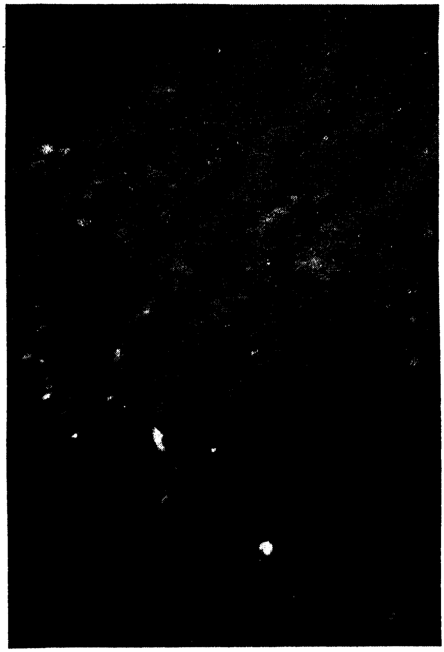

FIG. 30.—Rock, 90 fathoms, Coronado Canyon (Lat. 32°31.8′, Long. 117°21.3′). Possible small ravine cut in the rocky slope shown in the lower right corner.

THE GEOLOGY OF CATARACT FALLS, OWEN COUNTY, INDIANA

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Indiana University

ABSTRACT

At the double falls of Mill Creek near Cataract, Owen County, Indiana, more than 100 feet of Mississippian strata, ranging from the Lower Chester down through the entire Ste Genevieve and into the St. Louis below, are unusually well exhibited. The top of the Ste Genevieve limestone is marked by a thin limestone breccia and followed by a thin representative of the Aux Vases sandstone of the Lower Chester. In the middle of the Ste Genevieve is a fine-grained, calcareous sandstone, 23 feet in thickness, forming the face of the upper falls. This sandstone, described for the first time in Indiana, is correlated with the Rosiclare sandstone of southern Illinois and western Kentucky. Both the Aux Vases and the Rosiclare sandstones are present throughout the outcrop area of the Chester and Ste Genevieve formations in southwestern Indiana, though their recognition has long been delayed.

Near the village of Cataract, in northern Owen County of middle southwestern Indiana, Mill Creek, a sluggish stream draining approximately 250 square miles of glacial drift country, suddenly makes two plunges totaling more than 80 feet in two falls and the cascades which precede them. The upper falls has a sheer plunge of 20 feet and is preceded by noisy cascades, totaling 23 feet, over the rocky stream bed. The lower falls, about ½ mile downstream, has a fall of 17½ feet, preceded by rapids and cascades over 21 feet of exposed rock, all below the rock exposed in the upper falls. The double falls of Mill Creek are without equal in size elsewhere in Indiana, though the locality is not widely known and is only rather sparingly visited for its scenic interest.

The double falls near Cataract appear to have resulted from the presence of two preglacial rock ridges buried beneath Illinoian lacustrine deposits and encountered by the post-Illinoian Mill Creek superposed on them. During the retreating stages of the Illinoian glacial ice some barrier northwest of the Cataract locality permitted a large lake to develop, and the deposits accumulating in it built up an extensive lacustrine plain, known as the Quincy lacustrine plain, at an altitude of approximately 755 feet. Mill Creek, with its drainage leading generally westward, has cut a shallow valley into the lacustrine plain above Cataract Falls and a deep valley in a preglacial course below the falls. The buried bedrock ridges encountered near Cataract have prevented deep cutting into the lacustrine deposits in the upper section of the stream course, and the expansive lacustrine plain is nearly intact over an area exceeding 40 square miles east and northeast of the falls. Presumably, a buried, preglacial drainage course lies at some depth beneath the old lake plain. The two buried bedrock ridges near Cataract were apparently separated by a small preglacial valley leading northeastward between them to the major preglacial course, which the present stream has entered and re-excavated below the lower falls. The buried bedrock ridge encountered at the site of the upper falls is the main barrier of the present stream, having an altitude of about 740 feet. It has been cut deeply into on its lower side, about 20 feet below its former crest, by Mill Creek, revealing an excellent stratigraphic section at the falls site.

More than 100 feet of rock strata are well exposed in the two falls, the cascades, and the adjacent rock walls of the stream. Only casual references to these exposed strata occur in the literature

bearing on the region. They are referred to merely as belonging to the "St. Louis" or to the "Mitchell" limestones of Lower Carboniferous or Mississippian age. It does not appear that any detailed study previous to the present one has ever been made of the formations so well exposed in and about the falls. This is obvious when it is observed that the entire upper falls is over a massive sandstone bed and not over limestone beds, as the references imply.

A careful study of the rock formations exposed in the two Cataract falls, the cascades, and the immediate bluffs reveals the presence of two Chester formations, the entire Ste Genevieve, and some 10 feet or more of the upper part of the St. Louis limestone. All these strata are graphically presented in Figure 1 in proper stratigraphic arrangement, along with the measured thicknesses and the descriptions of the individual beds making up each of the stratigraphic divisions. The central interest is the massive calcareous sandstone, at least 23 feet thick, which composes the rock of the upper falls. This sandstone is in the middle of the Ste Genevieve limestone formation. The top of the sandstone is back of the lip of the falls, and the bottom is below the water level of the plunge pool and is not exposed. Careful examination indicates that it extends at least 2 feet and possibly as much as 3 feet below pool level. No such sandstone in the Ste Genevieve in Indiana has previously been described. It is unlikely that it has not been recognized as a sandstone in the conspicuous falls, though its stony whiteness gives it the appearance of limestone except on close inspection. The writer has known of its presence at the falls for more than twenty years, though no close study of it had been made until recently (see Figure 2).

As shown in Figure 1, the massive sandstone of the upper falls is in the middle of the Ste Genevieve. Above it are 22 feet of limestone strata, dominantly oölitic, belonging to the Ste Genevieve. These strata are well exhibited in the cascades above the falls. The top of the Ste Genevieve is well marked slightly above the level of the dam at the head of the cascades, 150 feet back from the falls, where the Aux Vases sandstone, the basal formation of the Chester series, rests upon it. The lower part of the Ste Genevieve is exposed in and near the lower falls, as shown in Figure 1. Here the lower limestone of the Ste Genevieve measures $30\frac{1}{2}$ feet in thickness. The whole of the Ste Genevieve, as exposed and measured in and near the two Cataract falls, is $75\frac{1}{2}$ feet in thickness, or possibly as much as 1 foot more. The sandstone in the middle composes nearly one-third of the thickness of the entire formation in the Cataract Falls locality. This sandstone is in the stratigraphic position of the Rosiclare sandstone of southern Illinois, and it is herewith correlated with it directly, though previously I have hesitated to make such a correlation because of its remoteness and have referred to it as the "Cataract Falls" sandstone. The 22 feet of limestone above it and below the widely distributed, but thin, Aux Vases sandstone (not previously described in southern Indiana) may be correlated with the Levias limestone, a name given to the limestone beds of the Ste Genevieve above the Rosiclare sandstone and below the Chester beds in western Kentucky by A. H. Sutton and J. M. Weller in 1932.[1] The limestone beds below the Rosiclare sandstone and above the St. Louis limestone have been designated as "Fredonia," and the beds of the Cataract

[1] "Lower Chester Correlation in Western Kentucky and Illinois," *Jour. Geol.*, Vol. XL (1932), p. 439.

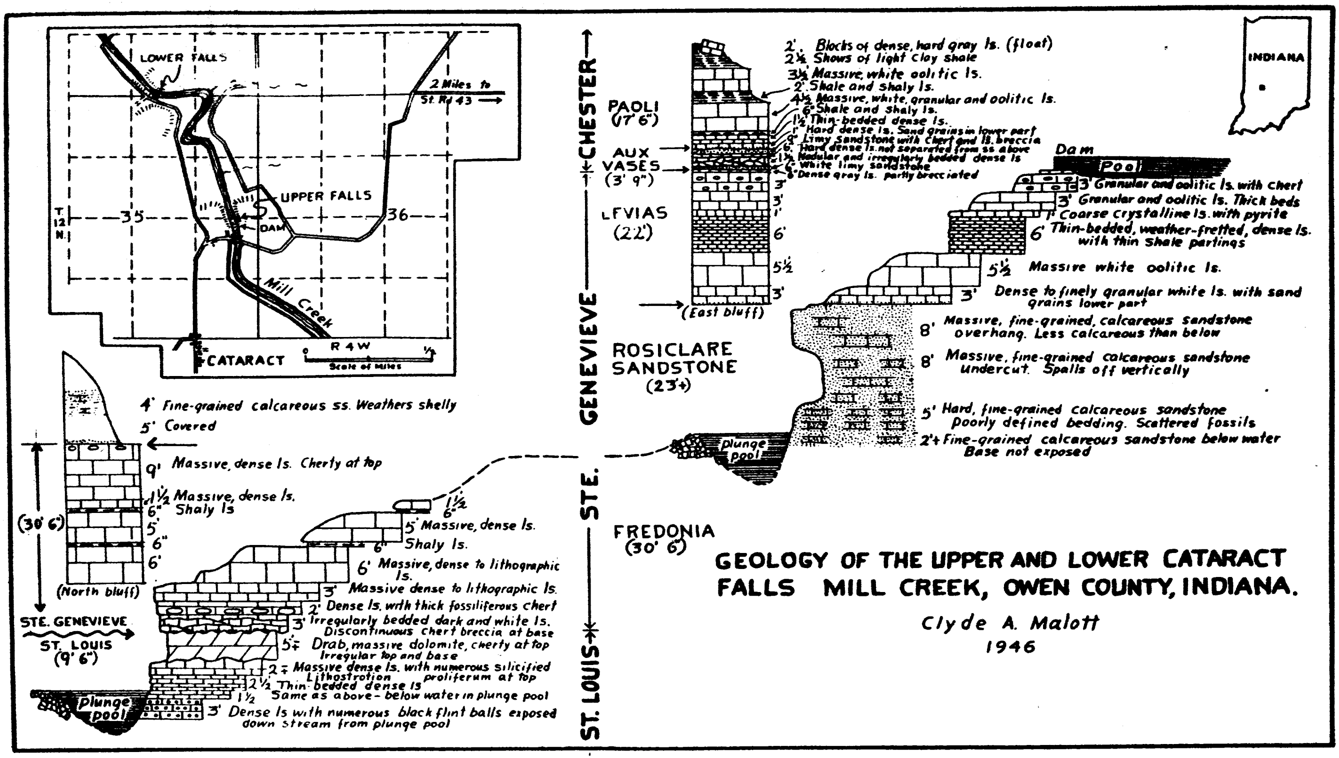
GEOLOGY OF THE UPPER AND LOWER CATARACT FALLS MILL CREEK, OWEN COUNTY, INDIANA.
Clyde A. Malott
1946
INDIANA
LOWER FALLS
UPPER FALLS
DAM
CATARACT
Mill Creek
2 Miles to St. Rd 43
35
36
T. 12 N.
R 4 W
Scale of miles
CHESTER
GENEVIEVE
STE.
ST. LOUIS
PAOLI (17' 6")
AUX VASES (3' 9")
LEVIAS (22')
ROSICLARE SANDSTONE (23'+)
FREDONIA (30' 6")
(East bluff)
(North bluff)
(30' 6")
STE. GENEVIEVE
ST. LOUIS (9' 6")
2' Blocks of dense, hard gray ls. (float)
2½ Shows of light clay shale
3½ Massive, white oolitic ls.
2' Shale and shaly ls.
4½ Massive, white, granular and oolitic ls.
6" Shale and shaly ls.
1½ Thin-bedded dense ls.
1' Hard dense ls. Sand grains in lower part
9" Limy sandstone with chert and ls. breccia
6" Hard dense ls. not separated from ss above
1½ Nodular and irregularly bedded dense ls
6" White limy sandstone
6" Dense gray ls. partly brecciated
Dam
Pool
3' Granular and oolitic ls. with chert
3' Granular and oolitic ls. Thick beds
1' Coarse crystalline ls. with pyrite
6' Thin-bedded, weather-fretted, dense ls. with thin shale partings
5½ Massive white oolitic ls.
3' Dense to finely granular white ls. with sand grains lower part
8' Massive, fine-grained, calcareous sandstone overhang. Less calcareous than below
8' Massive, fine-grained calcareous sandstone undercut. Spalls off vertically
5' Hard, fine-grained calcareous sandstone poorly defined bedding. Scattered fossils
2'+ Fine-grained calcareous sandstone below water Base not exposed
plunge pool
4' Fine-grained calcareous ss. Weathers shelly
5' Covered
9' Massive, dense ls. Cherty at top
1½ Massive, dense ls.
6" Shaly ls
1½
6"
5' Massive, dense ls.
6" Shaly ls.
6' Massive, dense to lithographic ls.
3' Massive dense to lithographic ls.
2' Dense ls. with thick fossiliferous chert
3' Irregularly bedded dark and white ls. Discontinuous chert breccia at base
5'± Drab, massive dolomite, cherty at top Irregular top and base
2'± Massive dense ls. with numerous silicified Lithostrotion proliferum at top
2½ Thin-bedded dense ls
1½ Same as above - below water in plunge pool
3' Dense ls with numerous black flint balls exposed down stream from plunge pool
Plunge pool

FIG. 1

Falls section occupying the same stratigraphic position may be called the "Fredonia limestone." These correlations are made on the stratigraphic chart (Figure 1).

The thin basal Chester sandstone formation, here correlated with the Aux Vases, at and slightly above the level of the dam back from the upper falls at Cataract is only 3 feet, 9 inches thick. It consists of two thin, limy sandstones, varying from a few inches to possibly 1 foot each in thickness, separated by irregular limestone beds and by more or less nodular limestone about 18 inches in thickness. The thin sandstone beds locally contain fragments of rounded and subangular dark limestone, which give the sandstone the appearance of a conglomerate in places. The lower thin sandstone locally rests on a brecciated limestone below it. This bed of brecciated limestone may be recognized at the top of the Ste Genevieve limestone in nearly every section where its stratigraphic position occurs throughout the outcrop belt in southern Indiana, and it is frequently present without the occurrence of any sandstone between it and the Chester limestone above. The upper thin sandstone layer composes the rock platform at the top of the cliff on the west side of Mill Creek a few feet above the level of the dam and for about 200 feet along the bluff above the cascades and the falls. Elsewhere through the outcrop belt it is not common to have two layers of sandstone separated by limestone marking the Aux Vases horizon.

FIG. 2.—View of the Rosiclare sandstone composing the middle part of the Ste Genevieve formation at the upper falls at Cataract, Owen County, Indiana.

A short distance downstream from the upper falls the rather massive Paoli limestone appears above the Aux Vases sandstone formation and forms the brow of the bluff. On the opposite or east side of the falls and cascades the Aux Vases sandstone formation is closer to the level of the dam and not so well exposed. The Paoli limestone above it is broken by two thin beds of easily weathered limy shale and a bed of gray shale near the top,

which show better on the east side than on the steep and rather inaccessible cliff of the west side, a short distance downstream from the falls. The thickness of the Paoli measures approximately 17 feet, though the top is very poorly exposed. The top 2 feet occur as blocks of limestone on the poorly exposed light shale, which is about 30 inches thick. This shale could possibly be interpreted as a thin representative of the Mooretown (sandstone) formation which succeeds the Paoli, but at other localities a similar shale bed has been observed near the top of the Paoli with a normal full thickness of the Mooretown and the succeeding Beaver Bend limestone above it. Near the site of the old Croy's Mill, about 3 miles downstream, both the Mooretown and the Beaver Bend formations are present and are 21 feet and 10 feet in thickness, respectively, and the Paoli limestone there has a shale bed near the top very similar to that shown at the upper falls at Cataract. The Paoli limestone, the Mooretown (sandstone), and the Beaver Bend limestone are correlated with the Renault of the Illinoian Chester.

In the lower Cataract Falls the uneven contact of the St. Louis and Ste Genevieve limestones is clearly shown approximately 10 feet above the water of the plunge pool and 8 feet below the lip of the waterfall. Patches of angular chert occur at the very base of the Ste Genevieve, which is distinctly whiter than the gray and dark beds of the St. Louis. Five or 6 feet below the contact are numerous dark, silicified *Lithostrotion prolitherum;* and, just below water level, the thin-bedded, dense St. Louis limestone is studded with the small masses and dark balls of flint 1–2 inches in diameter so characteristic of the upper part of the St. Louis. No evidence of colonies of *Lithostrotionella castelnaui* (=*Lithostrotion canadense*) was observed. This index fossil of the upper St. Louis, restricted to a single bed or zone, usually occurs about 20 feet below the contact with the Ste Genevieve; hence its horizon is not exposed at the lower falls. Large masses of porous, fossiliferous chert occur in the Ste Genevieve 3–4 feet above the base on the south side of the waterfall bluff. These chert masses are very similar to the fossiliferous Lost River chert beds of the lower part of the Ste Genevieve farther south in Indiana. The Rosiclare sandstone adjacent to the lower falls and cascades has retreated some distance back from the walls of the limestone gorge, since this sandstone weathers readily by solution, leaving the fine sand grains free to slump and wash away. However, it shows sparingly at one or two places on the north side of the falls, at and above the road on the south side, and in the turn of the road on the east side of the stream about ¼ mile southeast of the lower falls.

The Rosiclare sandstone of the Ste Genevieve described in the Cataract Falls section is present in numerous sections through southwestern Indiana, both north and south of Cataract. It varies considerably in its physical characteristics and is rather erratic in thickness, ranging from a few inches to a known section as great as 38 feet. It usually occurs 30–60 feet below the top of the Ste Genevieve, which is well marked by a limestone breccia and the common occurrence of the rather thin Aux Vases sandstone. The constant presence of the sandstone at the same horizon throughout the area of the outcrop of the Ste Genevieve to the Ohio River has led to its outright correlation with the Rosiclare sandstone of the southern Illinois section rather than to the proposal of a new name for it.

THE NATURAL STEAM AT LARDERELLO, ITALY

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ABSTRACT

The natural steam (vents, soffioni) of the Larderello and adjacent regions in Tuscany, Italy, was used in the largest pre-war natural steam power-plant installation in the world. The boric acid and other mineralizers in the steam were exploited in a large chemical industry. Many wells were drilled to tap the emanations delivered through fractures from a probable batholith freezing beneath.

Pneumatolysis is at work on a grand scale. This geologic occurrence merits more attention from American (and European) geologists than it has received. Data collected on brief field visits during early partial rehabilitation of the plants following bombing and demolition are presented.

INTRODUCTION

The use of natural steam from subterranean sources for generating power is an intriguing geological and engineering development not commonly realized. However, in Tuscany, Italy, at Larderello, about 12 miles south of the town of Volterra, a large-scale exploitation of natural steam has been developed since 1904 to such a stage in 1941 that over 100,000 kw. of electric power were being generated. Moreover, large quantities (over 10,000,000 kg. per year) of boric acid, borax, ammonium carbonate, carbon dioxide, and other chemicals were recovered from the vapors. During World War II the installations suffered severely from bombing and demolition, but reconstruction began in 1945 with the hope that eventually the future plants will exceed those of pre-war times. Insufficient attention has been given in American geological literature[1] to this striking geological occurrence of a probable freezing subjacent batholith, and even the most authoritative Italian publications on the subject have not been generally known or circulated because they were privately printed.

The Tuscan locality outstrips by far any similar occurrence in the world. Of the others, Iceland magmatic heat has been piped to an airport landing field and into Reykjavik, New Zealand has potential energy in her geyser region, and the "geysers" region of California north of San Francisco offers meager possibilities for the utilization of magmatic steam by man, but these do not have the potentialities of the large-scale, pre-war development at Larderello.

The material in this report comes from a variety of sources. As much firsthand information as possible was obtained from two brief visits to the area while the senior author was on geology-teaching field trips from the United States Army University (University Study Center) at Florence, Italy, during the fall of 1945. Inquiries were made of employees at Larderello and members of the science faculty at the Italian University at Florence. Serious handicaps imposed by the physical de-

[1] E. T. Allen and Arthur L. Day, "Steam Wells and Other Thermal Activity at the 'Geysers,' California," *Carnegie Inst. Wash. Pub. 378* (1927), p. 100.

Sir Roderick Impy Murchison, "On the Vents of Hot Vapor in Tuscany, and their Relations to Ancient Lines of Fracture and Eruption," *Jour. Geol. Soc. London*, Vol. VI (1850), pp. 367–84.

struction (about 90 per cent of production) of the power and chemical installations by the Allied bombing and German demolition, the possibility of unexploded mines remaining on the premises, the scattering of the employee personnel, and the effect of the change in political complexion of the Italian nation prevented collection of much desired data. Omissions are noticeable, but the reader is asked to be tolerant because of these difficulties. If nothing more is accomplished than to stimulate interest in American geologists touring Italy to visit and study the soffioni this note is worth while.

Published data (sometimes in conflict with those obtained in interview) were obtained from the private brochures written by the Messrs. Conti and generously donated through the good offices of Professor G. Abetti. The chemical problems were discussed with Professor G. Mannelli and with Captain Ludwig F. Audrieth, United States Army, professor of chemistry on leave, University of Illinois. The junior author, besides contributing geological data personally obtained, gave indispensable aid in bridging the language barrier which otherwise would have made this report impossible.

LOCATION AND HISTORY

The natural steam vents of Tuscany occur principally in seven groups distributed over an elliptical area of about 100 square miles[2] which lies 12 to 20 miles south of the town of Volterra, and about 20 miles inland from the Tyrrhenian Sea (Fig. 1). The seven groups which have been exploited, each including an area of several square miles, are Larderello, Castelnuovo, Serrazzano, Lustignano, Sasso, Lago, and Monterotondo. The largest power production and the main pre-war chemical plant were located at Larderello, which has given the name to the organization, Società Boracifera di Larderello, that controls the entire area.

The natural steam vents or blowholes, called soffioni, have been known since the thirteenth century when they were avoided as dangerous manifestations of satanic power. After about 1750 a beginning was made in the study of the geology of the region, and in 1777 Hubert Höfer, a chemist in the service of the Grand Duke of Tuscany, discovered and isolated boric acid from the waters issuing with the natural steam from the soil. Paolo Mascagni confirmed the occurrence of boric acid in 1799, but an independent boracic industry was not established until after 1827 when Count Francesco Larderel, a French exile, conceived the idea of utilizing the steam to concentrate the aqueous boric acid solutions. This proved successful, and the Larderello development was named in honor of Count Larderel.

Heat from the steam was used in various other stages of chemical industrial development, but no attempt was made to use it for generating power until 1904. Prince Piero Ginori Conti, then general director of the Larderello works, on July 4, 1904, fed a small steam engine with the natural steam and drove a small dynamo which lighted a few lamps. Conti was assisted by Professor Nasini of the University of Pisa and by Signor Ingegnere Bringhenti, who determined from measurements in 1905 that the steam issuing from the soffioni is superheated and maintains a practically constant temperature at a given output. Conti installed a larger steam engine in 1905, further enlarged the power plant with a turbine in 1912, and continued to add equipment at later dates.

[2] Prince Piero Ginori Conti, *The Natural Steam Power Plant of Larderello* (Firenze, Italy: Privately printed, 1924), p. 8.

A serious problem in power generation was presented by the abundance of gases other than steam which made condensation of the engine exhaust inefficient. Beginning in 1912, the natural steam was used to heat pure water whose steam was fed to the engines and then conventionally condensed. This procedure was continued until 1923 when Signor Bringhenti devised apparatus by which about 90 per cent of the contaminating gases were removed from the steam at only slight loss of temperature. By making appropriate adjustment in the condensers it was found more efficient to feed the processed steam directly to the engines than to continue the secondary evaporator stage; therefore, the Bringhenti process is still utilized.

The chemical industry which started with Höfer in 1777 with the production of boric acid and borax ("sale sedativo di Homberg" and "Tinkal," respectively) has evolved and grown along with the power developments until a dozen or more chemicals in different grades were manufactured at Larderello before the war. The 658-page treatise on the Tuscany boracic industry by Raffaello Nasini[3] and his students in chemistry is a monument to Nasini and an adequate expression of the researches and developments made on the chemical side.

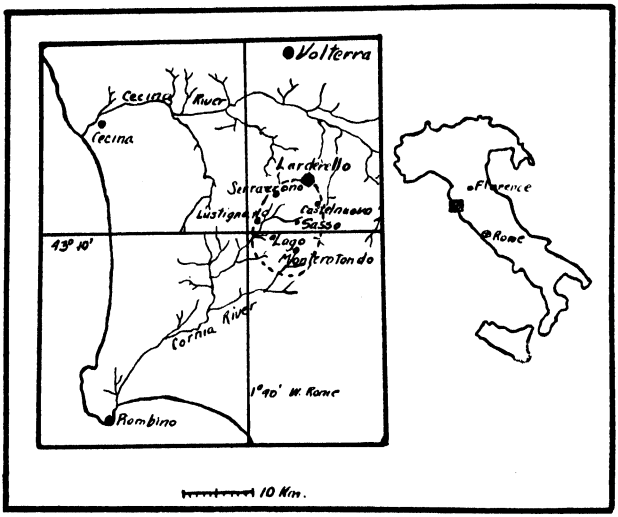

FIG. 1.—Location of Larderello and the soffioni area (modified after Conti)

GEOLOGICAL AND OTHER TECHNICAL DATA

The hot springs and bubbling puddles (lagoni), the steam vents (soffioni), and the drilled wells of notable vigor (soffionissimi) of Tuscany occur between the Cecina and Cornia rivers in a region of generally mature topography (Fig. 2). Surface rocks are mainly sediments of Eocene to Miocene age: limestones and shale at Larderello, sandstones at Sanno and Lago, limestone with chert at

3 Raffaello Nasini and Students, *I soffioni e i lagoni della Toscana e la industria boracifera, Associazione Italiana di Chimica* (Firenze, Italy: Publication sponsored by Piero Ginori Conti, 1930).

Monterotondo, but serpentine at Serazzano. The serpentine is probably a transported exotic in the Argile Scagliosa formation (Tertiary) which has been interpreted by Migliorini[4] as being tectonic rubble. Giovanni Conti[5] has emphasized that neither the age nor lithology of the surface rock influences the location or production of the steam. One expects rather that the positions of deep-seated faults determine these factors. As early as 1850, Murchison[6] reported that the vents issued along "ancient parallel lines of fracture," and De Stefani[7] later confirmed this conclusion. The present writers spent insufficient time in the field to work out the details of the structure in the region, but from a review of the large-scale geologic map and drill cores in the office at Larderello they sustain the belief that the steam arises along post-middle Tertiary faults. Local diversion of the steam by shallow fractures and divisional openings in the surficial rocks has probably widened the productive area above the deeper faults.

FIG. 2.—The power plant and chemical works at Larderello. Under normal operation all the steam would be utilized rather than blown into the air at the well locations.

Conti[8] wrote of "making hundreds of drillings in the last twelve years" (pre-

[4] Personal communication, fall 1945, from Carlo Migliorini, professor of geology, University of Florence.

[5] Giovanni Ginori Conti, *Utilizzazione dei soffioni boraciferi* (Firenze, Italy: Privately published, 1936), p. 77.

[6] P. 367 of ftn. 1.

[7] De Stefani, "I soffioni boracifera della Toscana," *Memorie della Società geografica Italiana* (1897), VI, 2, 410.

[8] P. 73 of ftn. 5.

ceding 1936) totaling about 40,000 meters in length, but conversation with staff members on the ground indicated that only about one hundred wells were significantly productive. Most wells were drilled about 250 meters deep, but the deepest reported was about 550 meters (literature) or about 900 meters (conversation with employees). Drilling had been done with both churn and rotary equipment, and an extensive expansion program was in progress when the war

TABLE 1

DATA ON A REPRESENTATIVE LARDERELLO WELL

Data	Metric	English
Diameter	480 mm.	19 in.
Depth	247 m.	876 ft.
Pressure	4.5 kg. per square centimeter	63.5 lbs. per square inch
Temperature	205° C.	410° F.
Yield	220,000 kg. vapor per hour	485,000 lbs. vapor per hour

started. Up to that time increased drilling had not lowered steam production. Definite information on the distance or patterns of spacing of wells was not available, but casual observation indicated a generally linear arrangement with holes separated several hundred feet.

Representative data of a well completed on March 26, 1931, are given in Table 1.[9]

Although most wells deliver steam at pressures from 2 to 5 atmospheres, one well was rated at 14 atmospheres with the valve partly open (Fig. 3). Probably the pressure on the closed well would have been higher, but it was considered unsafe to close it off entirely. Conti[10] reported that Nasini's experiments showed "that the steam issuing from the Soffioni is superheated. . . . . I cannot give any satisfactory explanation regarding the causes of this superheating."

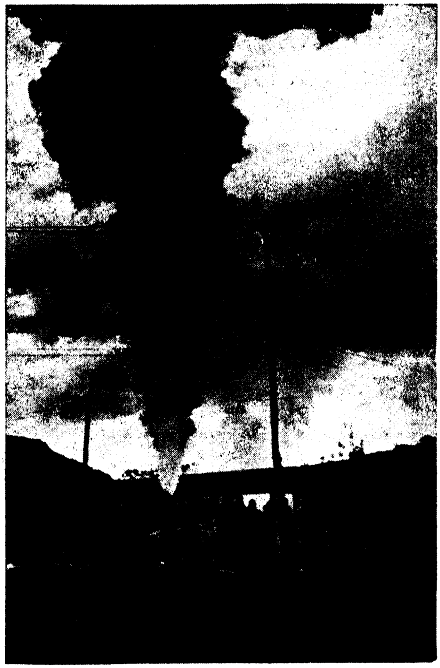

FIG. 3.—Natural steam escaping at approximately 4 atmospheres pressure from about an 18-inch pipe. The noise was deafening—note hands over ears of observers.

Allen and Day[11] explained similar superheat of the "geysers" in California, "This seems to mean that the steam as it rises from the depths is superheated and becomes saturated only after it has stood under pressure in the wells—probably because of the condensation of a portion of steam."

The steam from many wells is fed in to "supercentrali" power plants which had

[9] Personal communication from Professor G. Mannelli and Captain L. Audrieth, November, 1945.

[10] P. 13 of ftn. 2.

[11] P. 62 of ftn. 1.

a capacity of over 100,000 kw. in 1941. During 1938 a total of 202,610,000 kwh. of electricity was reported generated by the passage of 6,263,400 tons of steam through the plants. This power served most of the consumers in Tuscany and supplied the major need for the electrical railways between Livorno (Leghorn) and Rome. War destruction had cut the power production in late 1945 to about 10 per cent of pre-war capacity. Two

In practice, the boric acid is removed as a dilute solution in condensed steam and then further concentrated by evaporation. In subsequent stages the CO_2, NH_3, H_2S, etc., are taken out of the vapor. They may be purified and selectively recombined to produce a variety of carbonate or ammonium compounds. The details of the chemical processes and researches fill a volume (Nasini) in themselves.

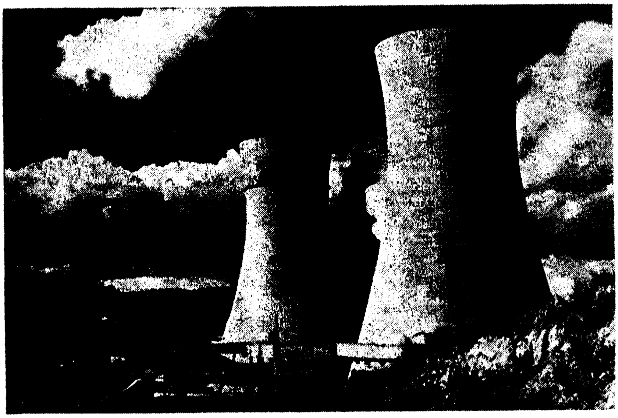

FIG. 4.—Two large condenser towers and the lower remnant of one destroyed by bombing

large condensing towers intact and one demolished by bombing are shown in Figure 4.

The chemical industry which started with the recovery of boric acid from the vapor was elaborated before the war to recover most of the "impurities" in the steam. The composition of the vapor, which is remarkably constant over the entire area and which has remained so despite continued drilling, is given[12] in Table 2. An analysis of the steam from well No. 2 of the California "geysers" locality[13] is included for comparison.

The gas residue, after condensation of the water vapor and elimination of boric acid and ammonia, is, according to Audrieth[14] and Mannelli, as shown in Table 3.

Annual production in the 1936–38 biennium ran about 7,000 to 8,000 tons for boric acid, about 4,500 tons for borax, and about 400 tons for ammonium sulphate. Other chemicals manufactured at Larderello include carbon dioxide and "dry ice," liquid ammonia, ammonium carbonate, ammonium bicarbonate, sodium perborate, ammonium chloride, manganese borate, and boron carbide.

The economic importance of these

[12] P. 64 of ftn. 3.

[13] Allen and Day, p. 76 of ftn. 1.

[14] Personal communication, 1945.

emanations justified a comprehensive geological and geophysical research program which was well under way prior to the war. A large-scale, highly detailed geologic map had been drawn of the thermal area, and drill cores taken from certain wells have been mentioned earlier in this report as surviving the ravages of war. Conti[15] reported the construction of a three-dimensional geological model from drilling data. A net of precise levels had been run to permit detection of any

TABLE 2

GRAMS PER KILOGRAM OF NATURAL VAPOR

Natural Vapor	Larderello	California Well No. 2
H_2O	945.87	986.86
CO_2	51.86	7.77
H_2S	0.86	0.35
H_3BO_3	0.5	less than 0.04
N_2	0.46	0.35 N_2 + A
CH_4	0.34	2.08
H_2	0.05	2.16
NH_3	0.1	0.18
He, Ar, etc.	1.0 cc. per kg. (with N_2)	

earth movements in the area. Gravimetric surveys were run using both a Sterneck pendulum and an Eotvos balance. Magnetometric data were collected. Preliminary earth-resistivity measurements using the Wenner method proved sufficiently interesting to stimulate additional research. The results were to be published when they were more complete. A local seismograph station was equipped with double horizontal-component apparatus and with two different vertical-component instruments having low and high sensitivities. When the war damage has been repaired it is hoped that these research programs will be continued.

[15] P. 74 of ftn. 5.

SOURCE OF THE STEAM

The source of the steam and gases of the Larderello region seems without much doubt to be magmatic. Ground water probably contributes some to the steam, but without the thermal energy of a magma there would be no soffioni. The Italians have attached high significance to the abundance of boric acid as a diagnostic characteristic. As early as 1897 De Stefani[16] pointed out that boric acid is not found in the superficial strata except when introduced locally and secondarily; its home is in the ancient granites. The high temperature and constant

TABLE 3

PER HUNDRED LITERS OF GAS

CO_2	93.0 liters
H_2S	2.4
H_2	1.8
CH_4	1.8
N_2	1.0
He, Ar, etc.	about 3 cc.

composition of the emanations also indicated that they were magmatic. Later D'Achiardi[17] elaborated on a possible source of the boron in (1) hypothetical deep-seated boron carbide or sulphide, (2) decomposition of borates of sedimentary origin, (3) borosilicates in serpentine, (4) tourmaline in granite, and (5) a product of volcanic (eruptive) fumaroles. He considered these hypotheses untenable and concluded that the soffioni were "vulcanico-geyseriania."

The following facts are significant in convincing the writers of a magmatic source for the steam in Tuscany:

[16] P. 410 of ftn. 7.

[17] Giovanni d'Achiardi, "Considerazioni critiche sulla origine dell'acido borico nei soffioni boriferi della Toscana," *Mem. Soc. Tosc. Sc. Nat. Pisa*, Vol. XXIII (1907), and "Guida al corso di mineralogia," *Pub. Francesco Vallardi Milano* (1925), p. 98.

1. Steam with superheat.
2. Steam pressure of at least 14 atmospheres.
3. Great volume of steam not affected appreciably by extensive drilling.
4. The abundance of boric acid and other mineralizer substances in the emanations.
5. The occurrence of the steam in large quantity distributed in localized areas over a district of about 100 square miles.

There seems to be little need to expand or elaborate the above evidence for magmatic origin. Some interesting speculation may be projected beyond the facts at hand. Perhaps a granitic batholith which has been freezing throughout a long period lies beneath Tuscany. The soffioni areas may be localized above cupolas if the cupolas are associated with faulting in the roof of the pluton.

From the figure of 6,263,400 tons of steam used for power in 1938 an approximate value of a minimum rate of solidification can be computed for the magma. Assuming that the magma contains 6 per cent[18] water in solution and taking a value of 2.67 for the density of granite and 62.5 pounds as the weight of one cubic foot of water, then approximately .008 cubic mile of frozen magma could supply the steam which was tapped in 1938 if the magma's entire water content became tapped steam.

$$\frac{100 \times 6{,}260{,}000 \times 2{,}000}{6 \times (5{,}280)^3 \times 2.67 \times 62.5} = .008 \text{ approx}.$$

About $5\frac{1}{2}$ cubic miles of granite, a small part of a pluton underlying an area of 100 square miles, could on the same assumption have furnished steam at the 1938 commercial rate for the 700 years of known activity. But most probably much more steam was released and dissipated through the rocks between the soffioni localities than was tapped by the wells. Moreover, the figure of 6 per cent for volatiles dissolved may not be correct in this case, and the computation may be far in error. It would be interesting to repeat solubility experiments like those of Goranson, using the Larderello emanations in place of pure water. Students of rock alteration and of mineralizer solutions should find the Larderello region one of fruitful interest.

If this region is underlain by a pluton now partially frozen, a spread of seismic prospecting shots taken over it might possibly reveal something of the size of the solidified top or the behavior of seismic waves within a possibly still-liquid interior. Perhaps other information pertinent to the general problem of batholiths might be obtained here. The authors believe a most significant geologic occurrence has escaped the attention of most American geologists.

[18] Roy W. Goranson, "The Solubility of Water in Granite Magmas," *Amer. Jour. Sci.*, Vol. XXII (1931), pp. 481–502.

GLACIATION IN THE DESERT RANGES, UTAH

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Ground and aerial reconnaissances in the desert-range area of Utah, comprising parts of Box Elder, Tooele, Juab, and Millard counties, disclose clear evidence of glaciation in only three ranges; some doubtful and contradictory evidence of ancient ice erosion or more recent nivation in several others; and no evidence of either glaciation or nivation in the remainder.

Typical and reasonably well-developed moraines are present in the Deep Creek Range and its extension, the Snake Range. Two sets of moraines are present in various valleys draining the slopes of Haystack Peak (Deep Creek Range); some scanty evidence suggests a third glaciation of much greater age. Wheeler Peak and Mount Moriah (Snake Range) were definitely glaciated, rough reconnaissances indicating two ages considerably separated in time. The younger glaciations in this general area are tentatively assigned to the "Later Epoch of Glaciation."[1] A thorough study of this area should be productive.

Poorly developed moraines, nivation scars, and several types of solifluction ridges are widespread in the Oquirrh Range. Most of this evidence seems older than that from the Deep Creek Range. Much of it leads to somewhat uncertain conclusions, suggesting surficial rearrangement, possibly due to frost action during relatively recent periods of increased precipitation.

One poorly preserved moraine, of apparent great age, deeply eroded and probably altered by faulting, is present on the southwest side of Deseret Peak (Stansbury Range) at an altitude of about 8,500 feet. Nivation and solifluction occurred in many places in the Stansbury Range and in its southern extension, the Onaqui Range.

Scattered evidence of nivation and solifluction was found in the Cedar, Newfoundland, and Thomas mountains. None of this evidence is clear or well developed. No evidence of glaciation or related processes was found by either aerial or ground reconnaissances in the Silver Island, Lakeside, Dugway, Fish Springs, Confusion, House, and Drum mountains; or on Granite Peak, Wig Mountain, Wildcat Mountain, and Stansbury Island.

Areas are named according to the General Land Office Map of the State of Utah (1937, 1 inch = 12 miles). Ranges not listed by name were not visited in connection with this reconnaissance.

[1] W. W. Atwood, "Glaciation of the Uinta and Wasatch Mountains," *U.S. Geol. Surv. Prof. Paper 61* (1909), pp. 1–15, Pl. I.

REVIEWS

Varvity in Danish and Scanian Late-Glacial Deposits; with Special Reference to the System of Ice-Lakes at Egernsund. By SIGURD HANSEN. ("Danmarks Geologiske Undersøgelse," II. Raekke, Nr. 63.) Copenhagen, 1940. Text, pp. 1–411 in Danish, pp. 413–78 English summary; figs. 20. Atlas of 45 plates and 2 maps.

The glacial clays in Denmark and southwestern Scania, the southernmost province of Sweden, were intermittently studied by Baron Gerard de Geer during 1906–17 and by the reviewer in 1918–20, but we were baffled by their poor, thin, and irregular lamination. However, since many lamina couplets fully resemble thin unquestionable varves, De Geer was convinced that most or all of them actually were varves and published graphs in 1926 and later. "Varve," "varvity," and "varved," it may be recalled, denote "annual deposit," "year-lamination," and "annually laminated." Geological conclusions based on these supposed varves met with strong opposition from Danish geologists. In 1927 the young Danes, Sigurd Hansen and S. A. Andersen, began to investigate these clays, after having studied geochronology under De Geer in Stockholm in 1925–26. Both Andersen and Hansen independently soon came to the conclusion that most of the lamina couplets measured by De Geer and me as varves represented only days or weeks (p. 422). Both published short papers, and Hansen undertook the detailed and comprehensive investigation quoted above.

The glacial clays in Scano-Dania were deposited in lakes and in the sea. The lakes were of two main kinds: glacial hillock lakes and marginal or regular glacial lakes (pp. 426–28).

The glacial hillock lakes are recorded by laminated clays occurring on top of the highest hillocks. The clay is called *Bakkeler*, *platålera*, and *Deckthon* and will here be named "hillock clay." The ancient level lake floors in a region rise to about the same heights, usually 5–20 meters above the surrounding land. The laminated clays are mostly a few meters thick, but some are as much as 10 meters. They rest normally on boulder clay, which forms the bulk of the hillocks. These are steep-sided and range from 100 meters to 4 km. in diameter. They occur in or just behind a morainic belt of knob-and-kettle topography or from 1 to 20 km. behind a marked ice border. The lakes were evidently ponded on all sides by ice and were windows in the ice, which must have been stagnant, though perhaps not broken into blocks. The cause of the melting of the windows over the highest hillocks is not known (p. 80).

The marginal ice lakes were dammed on one or more sides by ice, and a few may have been surrounded by ice. Some of these ancient lakes occurred in topographic basins, others did not (p. 84). Size, shape, and duration evidently varied. None of the Danish lakes seems to have exceeded 20 sq. km., while the glacial lake in central Scania was much larger and that of the southern Baltic was huge.

"Meltwater lakes"—regular lakes fed by meltwater from a glacier at some distance—are not surely recognized by Scano-Dania, but normal cold-temperate lakes, which received no meltwater, were present (p. 431). These were only lakelets or ponds. The surrounding arctic vegetation being sparse, mud was washed into the lakelets to form downwash clay (*Dryas* clay, *Anodonta* clay).

Hansen distinguishes two main types of ice-lake clays, A and B (p. 444). Type A is water-laid and stone-free but massive. Type B is stratified or laminated; a subtype is varved.

The massive or symminct clay, type A, occurs at only a few places (pp. 444, 445, 466). It was clearly a result of as fast settling of the fine particles that remained in the lake as of the coarse ones, and the problem of its formation is as follows: Why did all the fine clay, of which there must have been plenty dispersed through the lake water, settle before winter, so that not even a thin winter layer formed? Generally, symminct structure is a consequence of a high concentration of electrolytes; and it probably was also so in these cases. It is significant that these lake clays are more symminct than are the marine and brackish-water clays in Scano-Dania. Of the latter clays, most are stratified but unvarved, some are varved (locs. 136, 137,

142, 145, and 146), and a few are almost massive (locs. 130, 133–35).

Type B, which is laminated and, in Hansen's opinion, sometimes varved, embraces most of the glacial-lake clays in Scano-Dania. Two principal types of varvity are recognized. One, called the "normal" type or "Egernsund" type, is characterized by a greasy, conspicuous winter layer and a summer layer, which is several times thicker and mostly laminated. The varve thickness is usually 5–15 cm. (p. 469). This type is present in glacial Lakes Egernsund (several of locs. 1–23; Pls. 1–13, 35, 36) and Stenstrup (loc. 50; Pls. 18–20, 37, *L* and *M*), and at localities 43 (Fig. 32, Pl. 37, *J*), 47 (Pl. 37, *K*), 70 (Figs. 44–46), 86 (Pl. 26), 109 (Fig. 54, Pl. 38, *R*), 136 (Pl. 29; pp. 459, 470), 137, and 142, the last three deposits being brackish-water clays.

The glacial clays in the Egernsund region (Pls. 1–13, 35, 36, *E–H*), which are unquestionably varved, show within each varve irregular, mostly faint, laminae which probably were caused by small variations in currents and mud supply. Such faint laminae are regular features in varves formed near the point of mud inflow. Occasional laminae are prominent and comparable to similar ones in Lake Stenstrup. The clays of glacial Lake Stenstrup (Pls. 18–20, 37, *L* and *M;* pp. 241, 243) in which De Geer, Andersen, Hansen, and the reviewer apparently recognized the same units as varves, show, notably in the summer deposits, both faint and distinct laminae. The small and faint ones seem to be comparable to those common in the Egernsund clays. Light streaks of silt in the winter layers record influxes of mud after the colloidal clay had begun to settle in the early winter. On the other hand, the prominent light and dark couplets, such as those in varves 5 and 6, Figure *L*, and in varves 12 and 13, Figure *M*, many of which resemble thin varves, are not so readily explained. Each lamina couplet suggests a distinct inflow of mud, dispersion of the mud in the lake, and its separation by differential rates of sinking. The light, coarse fractions settled during and/or after the mud influx, depending on its duration; then the fine particles formed the dark lamina before any new large mud inflow took place. Judging from Figures *L* and *M*, there were mostly five to seven major influxes in melting season, or an average of one every 4–7 weeks, if this season comprised 7–8 months. The large temporary mud influxes could have been due to periodic ice melting or, more probably, to intermittent discharge into the lake of the main feeder stream, which much of the time then would have been diverted from the lake because its channel or tunnel was blocked by accumulated debris or collapsing dead ice.

Although the clay in the dark laminae probably is coarser than that in winter layers, it is not well understood how the clay laminae could form in the relatively short space of a month. Clay particles settle very slowly in ice-cold water because of its high viscosity; and, since the lake was ice-dammed, its temperature could not have risen much without causing its own destruction. The separate deposition of the relatively coarse fraction of the mud indicates low concentration of electrolytes. On the other hand, the water depth of some 20 meters (p. 252) was relatively small. Also, the amount of suspended fine mud was probably large, and the rate of sedimentation is proportionate to this quantity. Even though this attempt at explaining the marked laminae may be inadequate, these are surely subdivisions of varves, and the varvity recognized by Hansen seems certain in the clays of the listed deposits.

The second, so-called "zonary type," of varvity is defined by Hansen to comprise varves that have a lamination in the autumn and winter part as well as in the summer part and that are 2 dm.–1 meter thick (p. 470). It thus comprises clays having both a marked lamination by alternation of silt or fine sand and clay and a stratification of the second order, a zoning. The laminae range in thickness from mere streaks to 1.5 cm.; the couplets of silt and clay, which may resemble true varves in the grading of the material, measure up to 2 cm. (pp. 269, 454; Pl. 38, *N*). The zoning is produced by alternation of predominantly silty and of largely clayey beds, each consisting of a few to many couplets of laminae. The silty zones range from thinner than the clayey zones to several times thicker. The clayey zones vary in general composition from silty clay to fine clay. It is pairs of these zones, 2 dm.–1 meter thick, and comprising up to 75 lamina couplets, which Hansen regards as varves and recognizes at localities 29, 53, 59, 62, 76, 96, 145, and 146.

The zone pairs in some clay deposits are unquestionably varves. This holds foremost for those of localities 96 (Pls. 27, 38, *Q;* p. 309), 76, *D* (Fig. 48; p. 289), and 146 (Pls. 31–34). The first two were probably formed in marginal lakes; the last was deposited in brackish water.

At locality 96, Andersen and the reviewer had earlier measured the same couplets as varves.

Most other clays with zoning raise the question: Are the prominent varvelike lamina couplets, or are the zone pairs varves?

At locality 59 (Figs. 40–42; p. 264) there are thin marked laminae of silt or fine sand and clay, clay making up a little more than half. Especially when the clay is semidry and is viewed from a distance, a beautiful zoning is also visible. The clayey zones are as thick as, or thicker than, the silty zones, a pair averaging 3 dm. There seem to be 12–15 zone pairs in the deposit. In one case the silty zone contained 15–20 lamina couplets, the clayey one, 30–40 couplets. The silty zones may represent periods of relatively heavy inflows of mud, during which much of the fine fractions passed through the lake; the clayey zones, periods of smaller inflows during which most or all of the clay settled in the basin. The clay deposit forms the top of a relatively large hillock.

At locality 62 (Pl. 38, *N;* pp. 269, 454) there are distinct laminae of fine sand or silt and of clay. The material is well assorted and graded within the couplets, so that many of these resemble true varves. The thickest couplets measure 2 cm., of which 3–4 mm. are clay. There is also a subordinate, faint, and minute lamination. The zone pairs in this clay really resemble exceptionally thick varves, the clayey zones being distinct and relatively thin. The zone pair which is called "varve No. 5" by Hansen contains about 60 lamina couplets in the sandy zone, 30 cm. thick, and 15–20 in the clay zone, 6 cm. thick. At least 40 of the couplets in the sandy zone are varvelike. The clay deposit forms the top of a hillock, which is 300×400 meters in extent and rises 15 meters above its surroundings. It is 4–6 meters thick and contains probably 12–13 zone pairs.

The distinct lamina couplets at locality 62 were regarded as varves by De Geer (p. 423). In favor of well-developed couplets being varves is their resemblance to thin, true varves by the assortment of the material, its grading in a couplet, and the abrupt termination of the clay upward. Against their being varves are several conditions. They are not sufficiently distinctive but grade into pairs of faint streaks of light silt and dark clay which cannot be varves. The resemblance to varves might be largely superficial in that the dark lamina might consist of much coarser clay than do winter layers of varves; no comparative analyses have been made. That this is actually the case is suggested by the general coarseness of the material, considering the small thickness of the couplets. Varves so thin should consist of finer material. There are probably well over 700 varvelike couplets at locality 62. If these lamina couplets were varves, what prominent periodicity of 40–75 years would they record? What would the zone pairs signify?

Well-developed zone pairs such as those shown in Figure 42 and Plate 38, *N*, resemble exceptionally thick varves. The clayey zones frequently or normally have a marked upper limit (pp. 265, 269). The zoning represents a periodicity as distinct as the year. Considering that in the finer sediments of glacial Lakes Egernsund and Stenstrup the varves are mostly 7–10 cm. thick, the zone pairs can very well represent the annual deposit (p. 269). Varvelike lamina couplets occur in varves of the mentioned lakes (Pls. 36, 37). On the other hand, while the number of the varvelike couplets within a varve of Lake Stenstrup is but 5–7, it is some 40–75 at localities 53, 59, and 62. In the silty zone of zone pair 5, locality 62 (Pl. 38, *N*), there are about 40 major lamina couplets. Too few to record the day-and-night period, as Hansen believes (p. 270), each couplet would, instead, represent at an average 5–6 days, if the melting season was 7–8 months. At locality 59, the 15–20 lamina couplets in the silty zone and the 30–40 couplets in the clayey zone would mean a brief summer and a long autumn-winter with many moderate inflows. Either inflows would have occurred intermittently the year round, or no colloidal clay remained in the lake to settle in the winter; it could have been carried away by the outflowing water. The lamina couplets in localities 53 and 59 would have formed at a rate of 1 in every 5–7 days throughout the year. What marked climatic period could this be that caused, first, inflow of mud, then practical cessation of inflow, permitting the clay to settle? Or how could the influx be so periodic if intermittent by repeated diversions of the main feeder? How could varvelike couplets form in the short space of 5–7 days?

In making the choice between the lamina couplets and the zone pairs as varves, the coarseness of the material, the probable length of life of glacial hillock lakes, and the small depth and size of the lakelets should probably weigh most heavily. The two former speak against the lamina couplets being varves; depth

and size favor zone pairs. Thus coarse material goes with thicker varves than the lamina couplets. The tiny hillock lakelet of locality 62 could not well have existed for over 700 years. It does not occur in a prominent morainic line. An ice border is stationary because supply and wastage balance each other. The large Salpausselkä moraines of southern Finland represent, according to Matti Sauramo, only 660 years. The lamina couplets can hardly be varves. The zone pairs must represent the annual deposit, as Hansen holds.

The zone pairs are varves of an extraordinary type, associated with the peculiar mode of dead-ice waning in Denmark, southwestern Scania, northern Germany, and the East Baltic countries. The intermittent mud supply of the lakelets can have had at least two causes. It can have been a consequence of changing weather, such as warm spells followed by cold ones and rains followed by dry weather (p. 270). The day-and-night period seems too brief and would postulate many more lamina couplets than are present. The intermittent mud influx can also have resulted from temporary diversions or changes in the course of the supply stream.

The distinct lamination and the great number of the couplets postulate a thorough and rapid separation of the glacial mud into silt or fine sand and clay and a prompt deposition. The surprisingly quick settling of the clay fraction is at least partly explained by its relative coarseness and by the small depth of the lakelets. It may have been partly a consequence of large quantities of suspended material. But further studies are needed.

Decreasing distinctness of the annual stratification in Scano-Danian clays produces transitions to mere lamination. At localities 53 (Fig. 39) and 145 (Fig. 58) there is indistinct, at locality 76 (Fig. 47) doubtful, zonary varvity. At locality 82 (Fig. 49) there is a trace of zoning. At localities to be discussed below no varvity can surely be distinguished. The variation from distinct to unrecognizable varvity may depend mainly on the amount of fine clay that remained to settle in the lakelets during the winter (and autumn) (p. 384). This amount, in turn, depended on the quantity present in the inflowing glacial mud, on the portion that settled in the lake during the summer, and on the part that left the lake with the outflowing water.

Among the many clay deposits classified by Hansen as laminated but unvarved are localities 34, 94, and 95. All three deposits occur on top of hillocks. At locality 34 (Fig. 31, Pl. 36, *I;* p. 221) the clay contains laminae of rather coarse, rusty sand, which come out black on the photographs, but no strata that can be interpreted as winter layers. Locality 94 (p. 304), Maarum, is a hillock clay, 0.5×1.5 km. in extent, located in a marked morainic belt. The clay is beautifully laminated by alternating fine sand or silt and clay. At one place, where the clay is 6 meters thick, the couplets average 2 mm., so there may be some 3,000 of them. Hansen found no winter layers and no sure zones. De Geer has published 1,400 lamina couplets as varves; but it is extremely improbable that such thin and coarse couplets represent the year and that the hillock lakelet could last 1,400 years, not to say 3,000. Locality 95 (Pl. 38, *P;* p. 306), Dønnevaelde, is a hillock clay which is 300×400 meters in area and located in the same morainic belt as the preceding site. As seen in the photograph, the clay has beautiful lamination of at least two orders. Major couplets are marked by prominent dark clay laminae and are 0.5–1.5 cm. thick. In most of the coarse major laminae there are minute laminae, just as in some of those at locality 62 (Pl. 38, *N*). The major couplets were, in 1919, measured by me as varves, 100 of which were published by De Geer in 1935. However, since there may be as many as 600 major couplets in the clay, which is 6 meters thick, and since they resemble the short-term couplets at locality 62, they may not be varves.

Varves gradually decrease in thickness from the point of discharge of the glacial mud, and in large glacial lakes their distal portions may be only a few millimeters thick. The clays at localities 111 and 112 (Fig. 55; p. 322) in southeastern Scania are probably such distal varved deposits of the large glacial Baltic as De Geer recognized. The occasional layers of sand may be of local origin and caused by wave wash.

Hansen concedes varvity only at De Geer's localities in Lake Stenstrup and at Dronningmølle (Hansen's locs. 50 and 96; pp. 25, 254, 418, 451) and thus finds that the Swedish clay chronology at present terminates in northeastern Scania and that the prospects of extending it backward to Jylland and northern Germany are extremely slender (p. 474). Since most Danish glacial lakes seem to have existed for only 10–20 years, while Lakes Egernsund and Stenstrup lasted for about 50 years (pp. 446, 453) and since there is no positive evidence for

centuries—long halts in the retreat, Hansen estimates that the ice recession from the East Jylland moraine, the correlative of the south Pomerania stage, to northeast Scania took 2,000–3,000 years at the very most (p. 475). Since the ice border was in northeastern Scania about 13,500 years ago, the outer Pomerania stage would be dated at roughly 16,000 years. The belt being about 300 km. wide, a direct recession would have averaged 100–150 meters a year. However, the repeated oscillations of the ice border, which can represent long ages, make Hansen's time estimate seem rather low. The clays may be unreliable time indicators, since the ice-dammed lakes can have filled with sediments or can have disappeared before the ice really left the region. But, if Hansen's estimate is nearly right, a revision will be necessary of the reviewer's correlation between the ice waning in North America and in Europe (*Geol. Survey Can. Mem.* *168* [1931], p. 33).

Dr. Hansen is to be complimented on the conclusion of the difficult and time-consuming study of the Scano-Danian clays. He and Andersen seem to have discovered the true natures of their different stratifications, and Hansen has logically applied the principles found to a great many clay deposits and has synthesized the findings. When the conditions of formation of these clays become better known through further physical and chemical laboratory tests (pp. 463, 467), they should, together with Hansen's wealth of data, give new important suggestions on the climate and the mode of ice waning in this exceptionally interesting zone.

ERNST ANTEVS

Geology Applied to Selenology. By J. E. SPURR. Lancaster, Pa.: Science Press Printing Co., 1945. Part I: pp. x+112; figs. 23, pls. 4; Part II: pp. xiii+318; figs. 72, pls. 10.

Spurr's *Geology Applied to Selenology: The Imbrian Region of the Moon* appeared early in 1944, and a similar detailed study of another limited moon area had been contemplated by the author. But, as no other region proved so well fitted as the one already studied, he decided to consider the moon's surface as a whole in a more general analysis of its typical features. These two studies are now printed as independent volumes under one cover: I, "The Imbrian Plain Region of the Moon," and II, "The Features of the Moon."

"The surface of the moon as shown in photographs displays phenomena which are related to phenomena that we describe as vulcanicity on the earth. They are sufficiently like those of the earth to be recognized as due to somewhat similar causes, while in their differences they illustrate the differences between the two bodies" (Part I, p. x). This basic idea really guides the investigations, although, because the differences between the two bodies are so great, the author strives to approach the lunar problems without preconceptions. Working inductively, he reaches conclusions and develops interpretations principally from his own observations. But, committed to volcanological explanations, he gives no attention to the alternative hypothesis that the moon's depressions and much of its surface configuration have resulted from impacts of colliding bodies, except as this hypothesis is considered and found wanting in a two-page addendum to Part I and in a single-page addendum to Part II.

Spurr arranges the moon's depressions into four groups, from largest to smallest: maria, cirques, caldera-craters, and blowhole craters. These are carefully described in an analytical way and naturally furnish much of the material for the dynamic interpretations and inferred lunar history. Much study has been devoted to the patterns of the craters to bring out ground-plan characteristics, the distribution of ejectamenta, and other related features. The outlines of many of the cirques and caldera-craters are found to diverge from the circular or elliptical toward a polygonal shape, and a genetic significance is seen in the tendency toward the hexagonal form. The blowhole craters, however, form perfect circles.

Faulting has also received much attention, particularly (1) concentric faulting on crater rims, (2) transverse faulting radially outward from the Mare Imbrium, and (3) graben faulting. Especially interesting and instructive is the Imbrian fault system, which is represented graphically on an analytical chart.

The reader is conscious of going over a great deal of local, though essential, factual material; but interwoven with the descriptive detail is the author's interpretation. Explanations are not deferred while facts pile up. Consequently, as the treatment progresses from one area to another, the similarity of phenomena necessitates considerable overlapping discussion. This, however, is inevitable at the present stage of

selenology when the broader basic facts are still in the process of being recognized.

Assuming, first, a completely liquid moon, Spurr lists in his résumé a succession of fifteen changes, or stages of events, in its subsequent history. Greatly simplified, the interpreted sequence is about as follows:

In a thickening silicious crust many (largely meridional) fissures formed partly because of contraction. "On a large scale, these fissures became indurated, probably silicified, as to their walls, by deposition from escaping gases and other solutions. A vast number of craters formed between these fissures, using them as walls, and thrusting them aside in their growth" (p. 305). With continuation of the induration process and shrinkage attendant on crateroid activity, the lines and zones of induration yielded least, developing "knife-edged" septa and fissure ridges and forming the structural pattern which has been called the "Primitive Complex."

Other systems of intersecting faults and fissures developed, between which blocks of crust were uplifted, followed by subsidence. Some blocks subsided with little preliminary uplift. "This process resulted in graben and graben-craters, and, by development into the more nearly circular forms, in great craters, which were nevertheless genetically like the polygonal forms."

"The graben-crater period immediately preceded and accompanied the gradual rearing of the great Imbrian dome; and toward the central portion of this uplift the suppressed gas-charged lava (lunava) drifted. This lava migration involved shifting heat, which in some regions brought about the beginning of the extended general period of remelting. As the dome grew, there developed radial faulting in and around it." The center of the Imbrian dome later collapsed, forming the Imbrian basin. The rim, of mountainous proportions, settled, depressing also the crust outside and thus producing a marginal outer trough into which mare lava flowed. "While the mare lavas (lunavas) were still fluid, there were formed, in the now cooling or cooled remelted areas and elsewhere, abundant 'immature' caldera-craters and dish-craters; and, especially near the mares, some mature caldera-craters" (p. 306).

"The mare lunava gradually attained a crust. The crustal depressions or basins, especially those south of Imbrium, which depressions had been filled with lava and had already crusted over, experienced a further renewal of depression or sinking which broke the earlier mare crust and flooded the added areas with fresh lava—novabase." Later there were ash explosions from vents all over the moon, either associated with large craters, of which they were the final activity, or with small craters independent of larger predecessors.

"Shrinkage and Appression" is the title of chapter xxiii of Part II. In addition to general moon shrinkage, which Spurr considers responsible for much of the lunar relief, "there has been established the existence of an east-west contraction also, evidenced by appression, along north-south axes, of the slumped material around deflated and subsided craters. This condition appears a general and moon-wide one" (p. 263). The author also points out and emphasizes the fact that the low wrinkle (compression) ridges, visible on the surfaces of the maria, are predominantly oriented in a north-south direction although, in many places, their trends curve correspondingly with mare "shore-lines" (see Fig. 65, p. 270). Meridional alignment of these several features receives much consideration. But the lack of any great chain of mountain folds, so familiar on the earth, is barely mentioned (Part I, p. 108). Perhaps, however, the author, studying inductively the observed lunar features, did not feel concerned with possible features not seen, although rather peculiarly absent. Doubtless, also, we should expect to see less lunar than terrestrial folding because, with no great difference inherent in the rock material, the smaller body would have (on the scale-model principle stressed by M. K. Hubbert) much greater strength, relative to deforming forces operating within it, than the much larger earth. But, even so, the apparent lack of strong folding on the moon seems so strange that the possible controlling factors should receive critical investigation.

Geology Applied to Selenology is an important contribution to the ultimate solution of many lunar problems and perhaps also of certain geologic problems which should be illuminated by the light reflected from the moon. Spurr has indeed made a very painstaking study.

R. T. C.

Phosphates and Superphosphates. By A. N. GRAY. 2d ed. New York: Interscience Publishers, Inc., 1943. Pp. 416; tables 155. $7.00.

This pocket-size, leather-covered volume written in England and published under the

auspices of the International Superphosphate Manufacturers Association is a carefully compiled vôlume of statistical, historical, and general information on the rock phosphate and superphosphate industries. It contains little geological infomation but much information of value to the geologist seeking a fuller understanding of the economics of the phosphate industry. The first edition was published in 1930. In this second edition the statistical tables which make up over a third of the volume are brought up to 1939, the last pre-war year. The historical and general part has been greatly amplified.

Chapter i on phosphates and their uses traces the emergence of the present rock-phosphate industry as a result of the inadequacy of the supplies of bones for agricultural uses. The large rock-phosphate deposits of Estramadura, Spain, were known as early as 1808 but were not used for fertilizer. The use of rock phosphates for fertilizer dates from 1842, when a patent for their treatment by sulphuric acid was issued to the English agriculturalist, John Bennet Lawes. He used phosphatic nodules from Pliocene beds of England.

Since these early beginnings the bulk of all rock phosphate has been treated with sulphuric acid to produce superphosphates. It was not until World War I, when a shortage of acid existed, that any noteworthy amount of raw, untreated phosphate was used agriculturally, and the amount still so used is less than a million tons out of the total production of nearly 13 million (1939). The calcining of rock phosphate for the manufacture of phosphoric acid was also a development of World War I.

Chapter ii on the production of phosphates gives a brief world chronology of rock-phosphate mining. Notable among the later items in this chronology was the development, beginning in 1930, of the great apatite-bearing deposits of the Kola Peninsula in northern Russia. This apatite is concentrated by flotation and not only takes care of Russian needs but has provided some surplus for exportation to other European countries. The deposits yield six hundred thousand tons of concentrates annually, and the reserves are large. For the world as a whole the early development of the rock-phosphate industry was slow, and not until it was forty years old in 1887 did the production reach a million tons. The most rapid increase has been since 1919.

Chapter iii deals with composition and grades, and numerous representative analyses are quoted. While the most important item is, of course, the calcium-phosphate content, certain minor components, such as carbonates, iron, aluminum, and fluorine, have each a critical importance, which is fully discussed. It is noteworthy that considerable fluorine is recovered incidental to the manufacture of superphosphates.

Chapter iv is devoted to world distribution and reserves. Estimates of known reserves, based mainly on figures of the American Phosphate Rock Institute, for the world's four principal producing areas are:

	In Billions of Tons
North Africa (with Egypt)	3.7
United States of America	7.4
Islands in the Pacific and Indian oceans	0.2
Russia in Europe	5.5
Total	16.8

Minor areas outside these four raise the world's total to 17.4 billion tons. Estimates of "probable" reserves made in 1926 for the International Geologic Congress are immensely greater, totaling 467 billion tons. Of the Russian reserves, those of the Kola Peninsula apatite deposits are the largest, totaling over 2 billion tons.

Chapter v deals with consumption. World consumption in 1939 was approximately as follows:

	Per Cent
Europe, including Russia	56.5
North America	25.0
Australia and New Zealand	8.0
Asia and Africa	10.5
	100.0

It is noteworthy that many parts of the world use almost no rock phosphates; this is true of South America, Africa, and Asia except for Japan. The future will see increased demands in those areas.

There follows a chapter on trade in phosphates, and the next five chapters are devoted to superphosphates—their origins, history, production, consumption, and trade.

A chapter is devoted to double superphosphate, calcined phosphates, and phosphate of ammonia. A chapter deals with basic slag and another with phosphoric acid.

The last third of the book is devoted to

statistical tables, showing production, imports, exports, and consumption of phosphate rock and of superphosphates for all countries.

E. S. B.

The Rocky Mountains. By WALLACE W. ATWOOD. New York: Vanguard Press, 1945. Pp. 324; halftones 32; maps 3, with 8 cross-section drawings by ERWIN RAISZ. $3.75.

This is the third volume in the "American Mountain Series," edited by Roderick Peattie, its predecessors having treated *The Great Smokies and the Blue Ridge* for the southern Appalachians, and the Green, White, and Adirondack mountains as *The Friendly Mountains*. To the reviewer this new book brought back vivid recollections of the companionable Dr. Atwood, amid pack trains and around campfires, enjoying to the full an invigorating outdoor life and the scenic beauties of the Rocky Mountains, while engaged in unraveling their eventful geologic story. Many former members of his western field parties will enjoy similar memories, awakened by the experiences and studies which Atwood now brings to his readers, who may possibly wonder whether the Rockies have given the author keener satisfaction in discovering and interpreting geologic facts or as an appreciative camper, enthusiastic horseman, and mountain-lover. In the intertwining of the two elements lies the charm of the book.

The reader soon learns how a season of field work is conducted and how mountain structures and scenery tell their tales of past events. Then the mountain drama unfolds, bit by bit, as we move about in different parts of the Rockies, where the party sees many significant things and comes to understand and visualize how the mountains rose, were worn away, rose again, and since have been carved to their present state. Abundant humorous narrative mingles freely with artistic description and simple, effective exposition.

"Bonanza in the Rockies," the longest chapter, is the glamorous story of prospecting and mining, particularly in the pioneer days of high lights and deep shadows. The lively accounts of the discovery and rise of the different mining districts are entertaining as well as instructive. Indians, cattle roundups, cowboy songs, ranches, and tourists are the substance of another chapter, while the final one describes briefly the national parks in the Rocky Mountain region. Quite helpful is the folded relief map, by Erwin Raisz, of the mountainous belt and its environs from north of the Athabaska River to south of Albuquerque. Eight cross-section block drawings by Raisz give in generalized form the geologic structure of selected portions of the ranges. A geologic calendar for the Rocky Mountain region and a Bibliography complete the volume.

Some unfortunate errors should be noted. Facing page 100 are two photographic illustrations labeled: (1) "Devils Tower. An ancient laccolith in eastern Wyoming. This rises four hundred feet above the surrounding lands"; and (2) "Ship Rock, Arizona, and the Great Dyke." The Devil's Tower, however, rises fully twice the specified height above its immediate base and three times that height above the land a short distance away. Fortunately, on pages 121–22 the size of the tower is better appreciated, and the volcanic-throat interpretation supplants the laccolithic hypothesis. Ship Rock is in New Mexico, not in Arizona.

The mountain climber, whose numbers have been increasing rapidly in recent years, may feel that he is the forgotten man. The short, relatively simple walk from where the horses are left to the top of Uncompahgre in the San Juans (the one peak climbed) will hardly satisfy the mountaineer who carries rope and ice ax; he would call for a real job in the Tetons or the Canadian Rockies. But for most readers, hoping for pleasurable reading while acquiring substantial knowledge and true appreciation of this fine vacation country, *The Rocky Mountains* will be found well worth while.

R. T. C.

Topographical and Archaeological Studies in the Far East. By J. G. ANDERSSON. (Museum of Far Eastern Antiquities, Bull. 11.) Stockholm, 1939. Pp. 118; figs. 60, pls. 56, maps 9.

This volume presents the results of the author's studies in six widely separated parts of China, beginning with the Western Hills of Peking in 1914–20 and ending with the coast of Tonkin and Hong Kong Colony in 1938. The six areas of research are (1) Western Hills of Peking, (2) Honan, (3) Kansu, (4) western Szechuan, (5) Tonkin, and (6) Lantau Island, Hong Kong.

Following a period of deep vertical erosion

(Fen Ho) in northern China, the valleys were partially filled (Malan stage) with voluminous gravels interbedded in their upper part with sheets of loess. After the gravels came deposition of the main body of loess. Much later a new cycle of erosion (Pan Chiao) set in, trenching the Malan gravels to depths of 30–60 meters in some valleys and in places cutting through the Pleistocene gravels into the bedrock.

In 1937 the author was surprised to find gravel terraces of the Malan type also abundant in the high Tatsienlu region of western Szechuan near the Tibetan border. Arnold Heim had previously (1933) correlated one of these with moraines of the Mosimien stage of glaciation. Andersson thinks it premature to accept this correlation as proved but states that, if Heim's conclusion be fully substantiated, we should have a powerful means of correlating the late Pleistocene geology of China and the history of early man in Asia with the better known time record of Europe. All the other regions studied by Andersson are far from areas of glaciation, but he believes that climatic changes, together with some possible crustal warping, have been responsible for the sequence noted.

The Tonkin studies deal chiefly with limestone caves and with some open-air sites of early human habitation.

The volume is unusually well illustrated; many beautiful views testify to the photographic skill of the author.

R. T. C.

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A STUDY OF THE CHEMICAL ALTERATION OF BASALT IN THE KILAUEA REGION OF HAWAII[1]

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ABSTRACT

Chemical analyses of fresh and altered phases of basalt around Kilauea crater in Hawaii National Park indicate that two types of relatively rapid chemical decomposition are taking place. The first type occurs at steam vents where no sulphur dioxide is present. In this case silica and the soluble bases are leached away, leaving the hydrated oxides of aluminum and iron in the form of a characteristic lateritic product. The second type of decomposition is found at the *solfatara*, where sulphur dioxide is present to a variable extent. Here the alteration is accelerated, and the low pH results in the leaching-out of the alkali and alkaline earth elements, aluminum, and iron, leaving a siliceous yellow residue.

These indications have been confirmed by laboratory studies in which fresh rock was subjected to the action of steam, air, and carbon dioxide in various combinations over a period of 6 months.

A white deposit, found abundantly at the *solfatara* of Hawaii National Park, is of interest because it contains 12 per cent more sulphur trioxide than can be combined with the basic elements present. It appears to contain a melanophlogite with a vastly greater amount of "free" SO_3 than any reported.

INTRODUCTION

Rapid alteration of basalt is evident around the *solfatara* and steam vents in the Kilauea region of Hawaii. This alteration appears to be of two distinct types. The first type occurs around the steam cracks, where no sulphur dioxide is present in the vapors. Here sulphur deposits and white incrustations are absent; but brick-red crusts, several inches thick, are found on the rocks that are being attacked. These crusts, being very friable, break down to give a red lateritic residue.

The second type of alteration is found around the *solfatara*, where a more variegated display of color is evidence of greater chemical activity. Sulphur, gypsum, and red ochers are abundant. The older deposits in these areas are masses of yellow, friable material, with only traces of iron, as evidenced by pink colorations. All stages of change from the parent-rock to the final granular yellow deposits are visible.

Petrographically and chemically the mother-rock in both cases is essentially the same. General climatic conditions are the same. The only apparent difference is in the composition of the gases

[1] This work was conducted at the Hawaii National Park and at the University of Hawaii.

emanating from the cracks. A definite relationship, therefore, would be expected to exist between the composition of the gases and the composition of the altered rock. A field and laboratory investigation which gives evidence in support of this thesis is described in this paper.

HISTORICAL

Whitman Cross[2] describes the lavas of Kilauea as "predominantly olivine-poor basalts." Analyses show the total iron content to be fairly constant, ranging from 10.0 to 14.4 per cent. The aluminum content does not vary greatly with silicon and the individual bases. The most variable constituents in lavas of all types are magnesium oxide and calcium oxide, which range from 0.16 to 21.8 per cent and from 0.86 to 13.9 per cent, respectively. The alkalis are abundant in certain types, and even basaltic types may show more than 5 per cent. The presence of titanium in noteworthy amounts is characteristic of Hawaiian lavas, which average around 3 per cent titanium oxide. Phosphorus is present in only very small amounts.

The composition of the volcanic gases of Kilauea has been studied by A. L. Day and E. S. Shepherd,[3] T. A. Jaggar,[4] E. T. Allen,[5] and S. S. Ballard and J. H. Payne.[6] The gases issuing from the cracks are predominantly steam. Allen reports that the gas from drilled holes at the "Tourist Sulphur Bank" was 96 per cent steam, with carbon dioxide and sulphur dioxide following in order of magnitude. More recently the presence of hydrogen sulphide was detected prior to volcanic activity by J. H. Payne and S. S. Ballard.[7]

Walter Maxwell[8] in 1898 made the first study of soil formation in Hawaii as related to chemical breakdown. He noted the influence of acid vapors in breaking down lava to give various products, including gypsum, alums, red ochers, bauxite, and silicon-rich residues. Samples taken near acid vents were found to contain as much as 70 per cent silica.

Maxwell made a study of the effect of sulphur dioxide and steam on a sample of lava. From 52.9 gm. of lava he found that 1.221 gm. had gone into solution after 4 months. Analysis of the solid showed that silicon had been released by the gases, and the separation of aluminum and the alkalis as sulphates was evident. Iron was the least affected, showing that some of the iron-rich products were residual and not deposited. No explanation was offered for cases where iron was released and silicon was concentrated.

From analytical data from other sections of the Hawaiian Islands, Maxwell came to the conclusion that the lateritic soil, which is predominant in the islands, has been formed as a result of the chemical breakdown of the lava by sulphurous steam.

Hawiian soil-forming processes by weathering were studied by H. S. Palmer[9] in the Wahiawa region of Oahu.

[2] "Lavas of Hawaii and Their Relations," *U.S. Geol. Surv. Prof. Paper 88* (1915).

[3] "Water and Volcanic Activity," *Bull. Geol. Soc. Amer.*, Vol. XXIV (1913), pp. 573–606.

[4] "Magmatic Gases," *Amer. Jour. Sci.*, Vol. CCXXXVIII (1940), pp. 313–53.

[5] "Preliminary Tests of the Gases at Sulphur Banks, Hawaii," *Bull. Hawaiian Volcano Obs.*, Vol. X (1922), pp. 89–93.

[6] *Proc. Hawaiian Acad. Sci., 1937–1938; Bishop Museum Special Pub. 33* (1939), p. 5.

[7] "The Incidence of Hydrogen Sulfide at Kilauea Solfatara Preceding the 1940 Mauna Loa Volcanic Activity," *Science*, Vol. XCII (1940), pp. 218–19.

[8] "Lavas and Soils of the Hawaiian Islands" (Honolulu: Hawaiian Sugar Planters' Assoc., 1898). Pp. 116.

[9] *Soil Sci.*, Vol. XXXI (1931), pp. 253–65.

He found that water and oxygen are added during the conversion of rocks into weathered shells. The increase in oxygen accounted for the apparent increase in iron. Aluminum showed little change, while sulphur and titanium decreased appreciably, but only 10–30 per cent of the phosphorous, silica, ferrous iron, manganese, and alkalis of the original rock remained. The loss of magnesium and calcium was even higher.

EXPERIMENTAL

Collection of samples.—Figure 1 is a map of Kilauea crater showing the location of areas where collections were made in November, 1938. In area *A*, located at the south margin of the main bowl of the Kilauea floor, along the wall rock on the north side of the spit, the gases from the steam vents contain sulphur dioxide. Area *B* is half a mile east of this, and here the steam vents contain no sulphur dioxide. Photographs of the two areas are shown in Figure 2.

Loose and friable deposits were scraped from the rocks or scooped from the beds into specimen bottles. Weathered shells or crusts were chipped from the parent-rock by a hammer, and samples of the unaltered core of the same rock were taken at both locations. For comparative purposes a sample of fresh aa lava from the 1935 flow of Mauna Loa was obtained from Dr. T. A. Jaggar for analysis at the same time.

The following samples were subjected to complete analysis:

1. Parent-rock at sulphur dioxide vents (location *A*)
1*a*. Yellow residual decomposition product from No. 1
2. Parent-rock at steam vents (location *B*)
2*a*. Red residual decomposition product from No. 2
3. Aa lava from 1935 Mauna Loa flow
4. A white deposit from location *A*

Microscopic description.—The following microscopic description of the above samples is by Dr. Horace Winchell:

The parent rock of yellow residue, 1, is a normal olivine basalt such as may be found on any of the Hawaiian Islands in the older formations. The texture is intergranular porphyritic. The phenocrysts are feldspar (calcic labradorite with carlsbad and albite twinning and showing normal zoning) and partly iddingsitized olivine. The groundmass is composed of a felty network of plagioclase feldspar laths, of about the same composition as the outermost zones of the labradorite phenocrysts, showing carlsbad and albite twinning but no appreciable zoning. Granular pyroxene, somewhat altered in the specimen studied, fills most of the inter-feldspar space. Its composition is difficult to determine accurately because of the alteration and the fineness of grain-size, but probably lies in the augite-pigeonite portion of the system Diopside-Clinoenstatite-Hedenbergite-Al_2O_3. Iron "ores" (magnetite and/or ilmenite) are present as inclusions and as inter-granular crystals between and in the pyroxene grains. A little "ores" is included in marginal feldspar. There is good probability that both magnetite and ilmenite are present, though in the specimen studied, no definite criterion could be established. A very small amount of glassy material occurs with the pyroxene. Apatite probably occurs in tiny euhedral rods inclosed in the feldspar; no sure confirmation of the identity of the mineral could be obtained in the specimen studied, but experience (and presence of P_2O_5) shows apatite is a very likely guess.

The yellow residue, 1*a*, appears to consist mostly of opal. This is a hydrous, amorphous form of silica, with variable water content. The index of refraction, 1.435 (to the nearest .005), indicates the water content is of the order of 12% to 16%. The texture of the parent rock is preserved in the opalized material of a solid specimen of the yellow residue, 1*a*. Small amounts of melanophlogite, a *sulfur-trioxide bearing silica*, are present. The identification of this material rests on the index of refraction (1.46) and the fact that in two out of three trials, a definite blackening occurred when samples of the powder were heated before the blowpipe. An unidentified mineral of rather low birefringence and indices of refraction Np = 1.575, Nm about 1.585, and Ng at least 1.59, occurs in very small amount in the yellow

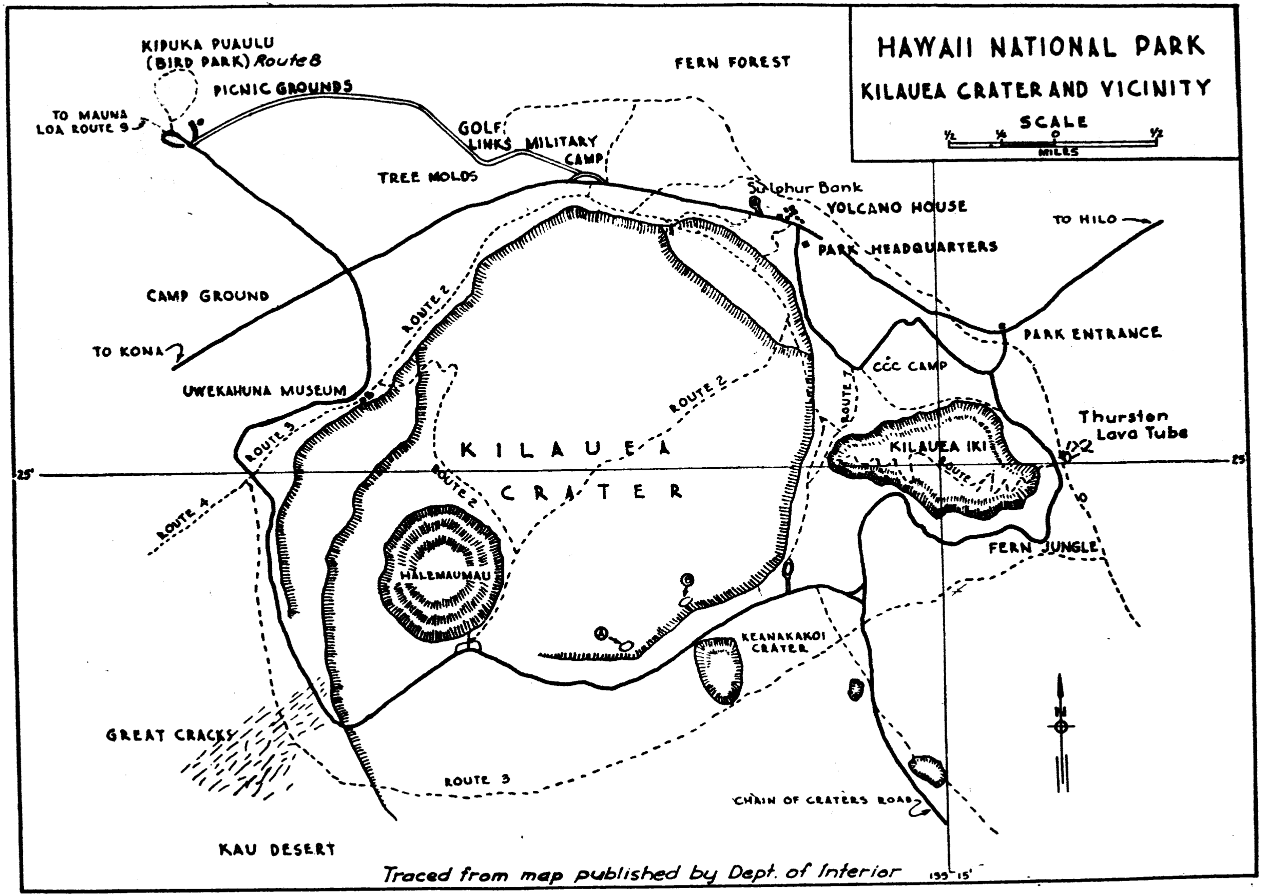

FIG. 1.—Map showing the location where samples were collected. *A*, region of steam and sulphur dioxide. *B*, region of steam activity, sulphur dioxide not detected.

A

B

FIG. 2.—*Top:* Area *A*, *solfatara; Bottom:* Area *B*, steam vents

powder. No mineral listed in standard optical tables and having a possible chemical composition as indicated by analysis, has these properties, even approximately. This mineral is present in such small amount that it would hardly be worth an attempt to separate and analyze a sample. It is possible that this or some other entirely overlooked mineral of high index and high birefringence and high dispersion may be present and contain the notable titania content shown in the analysis. The indices of refraction and lack of visible dispersion in the unidentified grains mentioned above suggest that these grains do not contain large amounts of titania.

The specimen of parent rock of red residue, 2, contains the following minerals: olivine, pyroxene (composition near diopside 50, hedenbergite 40, clinoenstatite and Al_2O_3 10), "ores," glass, and a fibrous, cryptocrystalline, nearly opaque material which may be altered or devitrified glass. These minerals are typical of a basalt practically identical with that described above under parent rock of yellow residue, 1, except that the larger amount of glass suggests the texture may be intersertal instead of intergranular, at least in part. Without actually studying a specimen of the rock itself, however, no definite statement can be made regarding the texture.

The red residue, *2a*, is about 95% finely divided, sub-homogeneous, reddish material showing slight evidence of anisotropism perhaps produced by the aggregation of anisotropic, submiscroscopic particles, since no extinction positions can be found in most grains. Very little can be determined optically because of the excessively fine grain of the powder. The red color is probably due to hematite, which is usually subtransparent to subtranslucent, and has an index of refraction appropriate to some of the powder. Clay minerals are undoubtedly present, but no detailed determination is practicable optically because of their finely divided state. An x-ray study would probably make possible the determination of some of the minerals present. A few grains of clear, anisotropic material of index considerably higher than 1.55 may be unaltered residual grains of pyroxene, or they may be some other mineral. No attempt was made to determine their exact nature because of their scarcity.[10]

[10] Private communication, May, 1940.

Spectrographic analysis.—The spectrographic analysis of the samples shown in Table 1 was made by Dr. S. S. Ballard at the Experiment Station of the Hawaiian Sugar Planters' Association.

Methods of analysis.—The methods of analysis were taken, for the most part, from H. S. Washington,[11] and from W. F. Hillebrand and G. E. F. Lundell.[12] Some modifications were introduced, and these are described in a thesis written by Mau at the University of Hawaii (1940).

TABLE 1

SPECTROGRAPHIC ANALYSIS OF THE SAMPLES

Amount	1	1a	2	2a	3
Major >1%	Si Na Ca Fe Al Mg K	Si Ti	Si Al Fe Ti Ca	Si Al Fe Ti	Si Ca
Minor 1%–0.01%	Ti Cr V Cu Mn Sr	Al Fe Mg Ca Na K Zr	Mg Mn Zr V Cu Na	Mg Mn Ca Cu Na	Fe
Trace <0.01%	Ni Co	Cr Mn	Cr Ni Co Sr Ba	Cr Ni Co	Mg Mn Na

Data.—The analysis of the parent and naturally decomposed rocks are presented in Table 2. These are average figures from duplicate samples.

It is apparent from these analyses that the two parent-rock specimens are essentially the same on the basis of chemical composition. This is of interest in view

[11] *The Chemical Analysis of Rocks* (3d ed.; New York: John Wiley & Sons, Inc., 1919). Pp. 271.

[12] *Applied Inorganic Analysis* (New York: John Wiley & Sons., Inc., 1929). Pp. 929.

of the fact that analyses by O. Silvestri[13] of rocks taken from the caldera walls of Kilauea do not show similar results. However, Cross[14] finds Silvestri's figures in many instances at variance with the normal for Hawaiian rocks. The analyses in Table 2 support the findings of Cross.

TABLE 2

SUMMARY OF THE ANALYSIS OF THE PARENT AND DECOMPOSED ROCKS

(In Percentages)

Constituent	Parent 1	Decomposed (SO_2) 1a	Parent 2	Decomposed (No SO_2) 2a
SiO_2	51.83	71.74	50.79	25.82
Al_2O_3	15.34	0.62	14.19	27.15
Fe_2O_3	0.98	0.10	2.14	19.45
FeO	7.85	0+	8.37	1.15
MgO	5.935	0.01	6.713	0.08
CaO	10.51	0.104	10.62	0.16
Na_2O	2.06	0+	2.10	0.26
K_2O	0.38	0+	0.869	0.12
$+H_2O$	1.03	1.85	0.49	11.88
$-H_2O$	0.34	11.26	0.25	9.05
CO_2	0.14	0.55	0.36	0.21
TiO_2	2.56	10.90	2.10	3.60
ZrO_2	0+	0.13	0.052	0+
P_2O_5	0.21	0+	0.23	0.28
SO_3	0.18	2.71	0.03	0.16
Cl	0.018	0.021	0.042	0+
S	0.22	0+	0.10	0.14
Cr_2O_3	0.057	0.037	0.073	0.201
V_2O_5	0.054	0+	0.059	0+
NiO	0.044	0+	0.016	0.023
CuO	0.087	0+	0.066	0.069
MnO	0.144	0+	0.329	0.138
SrO	0.02	0+	0.03	0+
BaO	0+	0+	0.01	0+
Total	99.989	99.968	100.029	99.941
Less O for Cl and S	− 0.117	− 0.009	− 0.069	− 0.070
Total	99.87	99.96	99.96	99.87

The changes occurring during the decomposition of the rocks are very significant. Where steam alone is present (Nos. 2 and 2*a*), it will be noted that the changes consist, aside from hydration, in a loss of silicon, a gain of aluminum, and an oxidation of ferrous to ferric iron. There is almost complete loss of magnesium, alkaline earths, and alkalis. Titanium, sulphur, and chromium show an apparent gain.

When sulphur dioxide is present (Nos. 1 and 1*a*), a vastly different change occurs. There is a marked gain in silicon, a considerable increase in titanium and sulphur, and practically a complete loss of all other constituents except water. Zirconium, which escaped detection in the chemical and spectrographic analysis of the parent-rock, has concentrated to a determinable amount.

TABLE 3

AVERAGES OF THE ANALYSES OF THE PARENT AND DECOMPOSED ROCKS RECALCULATED TO A TOTAL OF 100

(In Percentages)

Constituent	Parent 1	Decomposed (SO_2) 1a	Parent 2	Decomposed (No SO_2) 2a
SiO_2	51.90	71.77	50.81	25.859
Al_2O_3	15.36	0.62	14.20	27.19
Fe_2O_3	0.98	0.10	2.14	19.48
FeO	7.86	0+	8.37	1.15
MgO	5.943	0.01	6.713	0.08
CaO	10.53	0.04	10.63	0.16
Na_2O	2.06	0+	2.10	0.26
K_2O	0.38	0+	0.869	0.12
$+H_2O$	1.03	1.85	0.49	11.90
$-H_2O$	0.34	11.271	0.25	9.05
CO_2	0.14	0.55	0.36	0.21
TiO_2	2.56	10.90	2.10	3.60
ZrO_2	0+	0.13	0.052	0+
P_2O_5	0.21	0+	0.23	0.28
SO_3	0.18	2.71	0.03	0.16
Cl	0.018	0.021	0.042	0+
S	0.22	0+	0.10	0.14
Cr_2O_3	0.057	0.037	0.073	0.201
V_2O_5	0.054	0+	0.059	0+
NiO	0.044	0+	0.016	0.023
CuO	0.087	0+	0.066	0.069
MnO	0.144	0+	0.329	0.138
SrO	0.02	0+	0.03	0+
BaO	0+	0+	0.01	0+
Total	100.117	100.009	100.069	100.070
Less O for Cl and S	− 0.117	− 0.009	− 0.069	− 0.070
Total	100.00	100.00	100.00	100.00

In order to eliminate the effects of oxidation and hydration, the data in Table 2 have been recalculated to total 100, and one constituent has been assumed to remain constant. TiO_2 is held constant for the decomposition in the presence of sulphur dioxide (Nos. 1 and 1*a*) and Al_2O_3 in the presence of steam alone (Nos. 2 and 2*a*). Table 3 gives the analyses of Table 2, recalculated to 100;

[13] *Com. geol., Ital. boll.*, Vol. XIX (1888), pp. 128–47, 168–96.

[14] See ftn. 2.

Table 4 shows the relative changes in the presence of sulphur dioxide, holding TiO_2 constant; and Table 5 the relative changes in the presence of steam alone, holding Al_2O_3 constant.

the constituents except silica and titania have been leached away. In the absence of sulphur dioxide, the iron and aluminum remain, along with the silica and titania. Thus conditions of such high

TABLE 4

RELATIVE CHANGES RESULTING FROM DECOMPOSITION BY STEAM IN PRESENCE OF SULPHUR DIOXIDE, ASSUMING TiO_2 CONSTANT

(In Percentages)

Constituent	Change in Original Rock			Change in Each Constituent		
	I Remaining	II Loss	III Gain	IV Remaining	V Loss	VI Gain
SiO_2	16.9	35.0	....	32.5	67.5	....
Al_2O_3	0.15	15.2	....	0.08	99.0	....
Fe_2O_3	0.02	0.96	....	2.04	98.0	....
FeO	0	7.86	....	0	100	....
MgO	0+	5.95	....	0	100	....
CaO	0.01	10.5	....	0.09	99.9	....
Na_2O	0	2.06	....	0	100	....
K_2O	0	0.38	....	0	100	....
$+H_2O$	0.43	0.60	....	41.8	58.2	....
$-H_2O$	2.65	....	2.31	779	....	679
CO_2	0.13	0.01	....	92.9	7.14	....
TiO_2	2.56	0	....	100	0	....
ZrO_2	0.13	....	0.13	0	....	∞
P_2O_5	0	0.21	....	0	100	....
SO_3	0.65	....	0.46	356	....	256
Cl	0+	0.02	....	0	100	....
S	0	0.22	....	0	100	....
Cr_2O_3	0.01	0.05	....	16.7	83.3	....
V_2O_5	0	0.05	....	0	100	....
NiO	0	0.04	....	0	100	....
CuO	0	0.09	....	0	100	....
MnO	0	0.14	....	0	100	....
SrO	0	0.02	....	0	100	....
BaO	0	0.02	....	0	100	....
Total	23.5	79.4	2.80	....	....	....

In Tables 4 and 5 the last three columns give the percentage remaining, lost, or gained by each constituent referred to its total amount as 100. Figures 3 and 4 show graphically the changes taking place for the major constituents.

The differences in the two types of decomposition are striking. In the presence of sulphur dioxide, practically all

acidity as obtain around the *solfatara* give rise to the siliceous residual deposits. Decomposition by steam and weathering alone give the red lateritic residues, which are high in iron and alumina.

Moisture is abundant at Kilauea, and this plays an important role in speeding up the decomposition processes in that area. In drier regions the same processes

occur at a much slower rate, so that soil formation may be a matter of years rather than weeks, as it is at Kilauea.

LABORATORY DECOMPOSITION

In order to test these findings in the laboratory, studies were made of the effect of various gases on fresh rock. The parent-rock for these studies was a sample of aa lava collected from the 1935 flow of Mauna Loa by Dr. T. A. Jaggar. This sample was used because it had been subjected to no weathering action, having been collected hot while the lava was still flowing at a rate of 100 feet per hour.

The rock sample was prepared by crushing in a steel mortar and sifting. Material passing through a No. 16 sieve but retained by a No. 30 sieve was used, 50-gm. samples of the rock were suspended in platinum gauze cylinders in a 2-liter flask, as illustrated in Figure 5. The flask, fitted with a reflux condenser, was maintained at the boiling-point of water by immersion in an oil bath. Gases were introduced through side tubes at the rate of approximately 0.1 cc. per second.

Five separate samples were treated with the following combinations of gases for an uninterrupted period of six months.

TABLE 5

RELATIVE CHANGES RESULTING FROM DECOMPOSITION BY STEAM IN ABSENCE OF SULPHUR DIOXIDE, ASSUMING Al_2O_3 CONSTANT

(In Percentages)

Constituent	Change in Original Rock			Change in Each Constituent		
	I Remaining	II Loss	III Gain	IV Remaining	V Loss	VI Gain
SiO_2	13.5	37.31	....	26.6	73.4	....
Al_2O_3	14.2	0	....	100	0	....
Fe_2O_3	10.2	....	8.03	475	....	375
FeO	0.60	7.77	....	7.17	92.8	....
MgO	0.04	6.67	....	0.60	99.4	....
CaO	0.08	10.5	....	0.75	99.2	....
Na_2O	0.14	1.96	....	6.67	93.3	....
K_2O	0.06	0.81	....	6.90	93.1	....
$+H_2O$	6.21	....	5.72	1,270	....	1170
$-H_2O$	4.72	....	4.47	1,890	....	1790
CO_2	0.11	0.25	....	30.6	69.4	....
TiO_2	1.88	0.22	....	89.5	10.5	....
ZrO_2	0	0.05	....	0	100	....
P_2O_5	0.15	0.08	....	65.2	34.8	....
SO_3	0.08	....	0.05	267	....	167
Cl	0	0.04	....	0	100	....
S	0.07	0.03	....	70.0	30.0	....
Cr_2O_3	0.10	....	0.03	143.0	....	42.8
V_2O_5	0	0.06	....	0	100	....
NiO	0.01	0.01	....	50.0	50.0	....
CuO	0.04	0.03	....	57.1	42.9	....
MnO	0.07	0.26	....	21.2	78.8	....
SrO	0	0.03	....	0	100	....
BaO	0	0.01	....	0	100	....
Total	52.2	66.1	18.3	....	....	....

Sample
- I. Steam and air
- II. Steam and carbon dioxide
- III. Steam, air, and carbon dioxide
- IV. Steam, air, and sulphur dioxide
- V. Steam, air, carbon dioxide, and sulphur dioxide.

The samples were then removed for examination. Samples I, II, and III showed no visible change. Samples IV and V, however, were covered with a white deposit within 3 months and at the end of 6 months had a heavy deposit on the lower portion, as shown in Figure 6.

The analysis of the original rock and of the five samples subjected to the action of the various gases are presented in Table 6. It will be noted that the analysis of the original rock is very similar to that of the parent-rocks in Table 2. The 1935 sample has a higher ferric oxide content and a lower percentage of total water, however. Exposure to the air in a small piece at the high temperature of the lava flow probably accounts for the higher ferric oxide content, while the low water content would be expected for the same reason and also because there had been no hydration due to weathering. The possibility of ascertaining the relative age of lava flows in a given area by measuring the extent of the hydration is indicated.

Samples I, II, and III, where no sulphur dioxide was present, show little change from the parent-rock. There is some increase in the ferric oxide content with a corresponding decrease in the

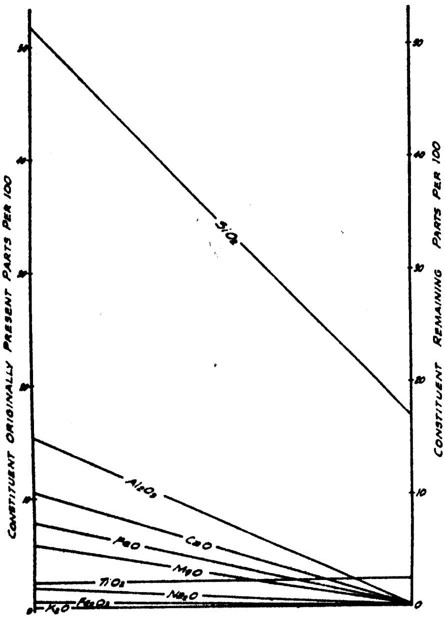

FIG. 3.—Comparison of changes produced by steam in the presence of sulphur dioxide. TiO_2 is held constant and the changes in other constituents compared with it.

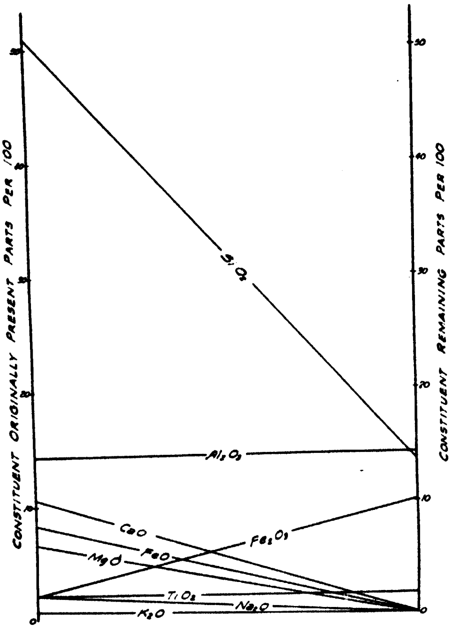

FIG. 4.—Comparison of changes produced by steam in the absence of sulphur dioxide. Al_2O_3 is kept constant and the changes in other constituents compared with it.

ferrous oxide content, however, as well as a slight increase in total water and a small loss of alkalis and alkaline earths.

In Samples IV and V the presence of the sulphur dioxide has greatly altered the composition. In order to obtain a better picture of the changes which have taken place, the analyses of the parent-rock and Samples IV and V have been recalculated to 100 per cent, as shown in Table 7; then in Tables 8 and 9 the titania content has been held constant, and the percentage change has been calculated as previously with the naturally decomposed material.

These changes are shown graphically in Figures 7 and 8. It is seen that there has been a gain both in water and in sulphur trioxide. All the other constituents show substantial losses. Magnesia shows the highest loss, reaching 76 per cent in Sample V. Silica remains with the smallest loss, with a maximum of 28 per cent in Sample IV. The changes are the same that occurred in the rock undergoing natural decomposition at the *solfatara*. If the process were allowed to continue, a final residue similar to that found naturally would undoubtedly remain. The evidence from the laboratory work confirms, therefore, the field observation with regard to the breakdown mechanism. Some evidence as to the speed of this breakdown is given likewise.

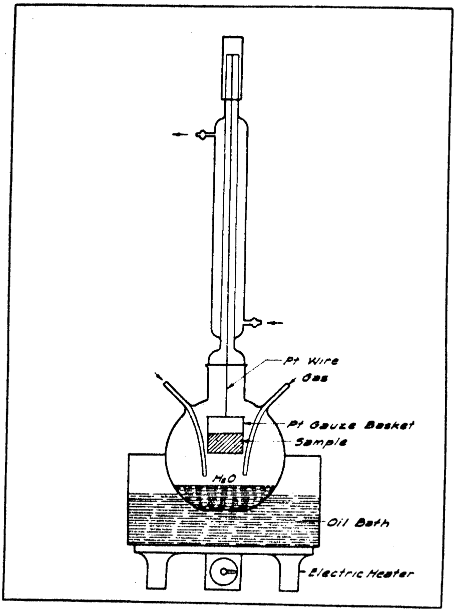

FIG. 5

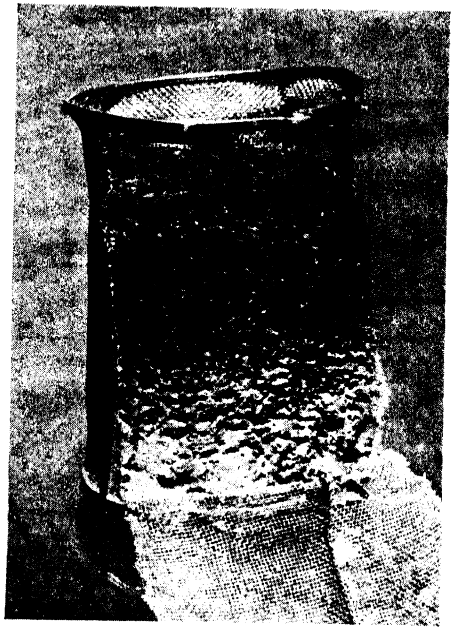

FIG. 6.—Decomposition of lava sample after 6 months of exposure under the combined action of steam, air, and sulphur dioxide. Note the lower zone, which is white with soluble salts leached out from above.

THE WHITE DEPOSIT

The residues in area *A*, where sulphur dioxide is present, are characterized by the presence of white incrustations and deposits. In some instances one can reach beneath lava ledges or into cracks and

TABLE 6

ANALYSES OF 1935 ROCK AND SAMPLES SUBJECTED TO VARIOUS GASES FOR 6 MONTHS

(In Percentages)

Constituent	1935 Parent-Rock	I Subjected to H_2O, Air	II Subjected to H_2O, CO_2	III Subjected to H_2O, Air, CO_2	IV Subjected to H_2O, Air, SO_2	V Subjected to H_2O, Air, SO_2, CO_2
SiO_2	52.73	52.75	52.53	52.89	44.66	51.83
Al_2O_3	15.57	15.79	16.01	15.97	7.97	7.71
Fe_2O_3	3.95	4.39	4.86	4.52	3.10	3.24
FeO	6.33	6.27	5.39	5.61	2.36	1.84
MgO	7.28	7.14	7.04	6.99	2.98	2.03
CaO	9.21	9.08	9.20	9.18	6.74	8.65
Na_2O	1.90	1.82	1.69	1.80	1.31	1.40
K_2O	0.25	0.20	0.22	0.19	0.16	0.17
$+H_2O$	0.10	0.13	0.13	0.14	5.00	4.01
$-H_2O$	0.04	0.08	0.05	0.06	8.21	4.05
CO_2	0.10	0.0+	0.08	0.03	0.0+	0.02
TiO_2	2.13	2.07	2.15	2.22	2.51	2.48
SO_3	0.10	0.10	0.08	0.04	15.08	12.51
Total	99.69	99.82	99.43	99.64	100.08	99.94

TABLE 7

ANALYSES OF THE 1935 ROCK AND SAMPLES IV AND V FROM TABLE 7, RECALCULATED TO TOTAL OF 100

(In Percentages)

Constituent	1935 Parent-Rock	IV Subjected to H_2O, Air, SO_2	V Subjected to H_2O, Air, SO_2, CO_2
SiO_2	52.89	44.64	51.86
Al_2O_3	15.61	7.96	7.72
Fe_2O_3	3.96	3.10	3.24
FeO	6.35	2.36	1.84
MgO	7.31	2.98	2.03
CaO	9.24	6.72	8.66
Na_2O	1.91	1.31	1.40
K_2O	0.25	0.16	0.17
$+H_2O$	0.10	5.00	4.01
$-H_2O$	0.04	8.20	4.05
CO_2	0.10	0	0.02
TiO_2	2.14	2.51	2.48
SO_3	0.10	15.06	12.52
Total	100.00	100.00	100.00

obtain handfuls of the pure white mass. The same material was found in the laboratory decomposition in the presence of sulphur dioxide. This residue has been variously described as gypsum and silica. Examination and analysis shows it to be a unique mineral.

Dr. Horace Winchell describes the deposit as follows:

The white deposit is composed mainly of gypsum and melanophlogite, with a very small amount of opal, probably less than 5%. The gypsum composes more than half of the sample. It is easily identified microscopically by its cleavages, optic orientation, and indices of refraction (Nm about 1.522). Melanophlogite is identified by its isotropic nature, its index of refraction 1.460 (published accounts of this mineral give 1.461 to 1.45?), and by the fact that it turns dark when heated before the blowpipe. The chemical analysis of the white powder indicates that the melanophlogite must contain considerably more sulfur trioxide than that described, however, and this possibility should be studied further, with chemical and x-ray studies and perhaps further optical work.

The chemical analysis given in Table 10 shows that the essential constituents are sulphur trioxide, silicon dioxide, calcium oxide, and water. It is obvious

TABLE 8

RELATIVE CHANGES IN SAMPLE IV RESULTING FROM LABORATORY DECOMPOSITION BY STEAM, AIR, AND SULPHUR DIOXIDE, ASSUMING TiO_2 CONSTANT

(In Percentages)

Constituent	Change in Original Rock			Change in Each Constituent		
	I Remaining	II Loss	III Gain	IV Remaining	V Loss	VI Gain
SiO_2	38.1	14.8	....	71.9	28.1	....
Al_2O_3	6.79	8.82	....	43.5	56.5	....
Fe_2O_3	2.64	1.32	....	66.7	33.3	....
FeO	2.01	4.34	....	31.8	68.2	....
MgO	2.54	4.77	....	34.8	65.2	....
CaO	5.74	3.50	....	62.1	37.9	....
Na_2O	1.12	0.79	....	58.6	41.4	....
K_2O	0.14	0.11	....	56.0	44.0	....
$+H_2O$	4.26	....	4.16	4,260	....	4,160
$-H_2O$	6.99	....	6.95	17,500	....	17,400
CO_2	0	0.10	....	0	100.0	....
TiO_2	2.14	0	....	100	0	....
SO_3	12.8	....	12.7	12,800	....	12,700
Total	85.3	38.6	23.8	....	....	....

TABLE 9

RELATIVE CHANGES IN SAMPLE V RESULTING FROM LABORATORY DECOMPOSITION BY STEAM, AIR, SULPHUR DIOXIDE, AND CARBON DIOXIDE, ASSUMING TiO_2 CONSTANT

(In Percentages)

Constituent	Change in Original Rock			Change in Each Constituent		
	I Remaining	II Loss	III Gain	IV Remaining	V Loss	VI Gain
SiO_2	44.8	8.14	....	84.6	15.4	....
Al_2O_3	6.66	8.95	....	42.7	57.3	....
Fe_2O_3	2.80	1.16	....	70.7	29.3	....
FeO	1.59	4.76	....	25.0	75.0	....
MgO	1.75	5.56	....	23.9	76.1	....
CaO	7.47	1.77	....	80.8	19.2	....
Na_2O	1.21	0.70	....	63.4	36.6	....
K_2O	0.15	0.10	....	60.0	40.0	....
$+H_2O$	3.46	....	3.36	3460	....	3360
$-H_2O$	3.49	....	3.45	8730	....	8630
CO_2	0.02	0.08	....	20.0	80.0	....
TiO_2	2.14	....	....	100	0	....
SO_3	10.8	....	10.7	10800	....	10700
Total	86.3	31.2	17.5	....	....	....

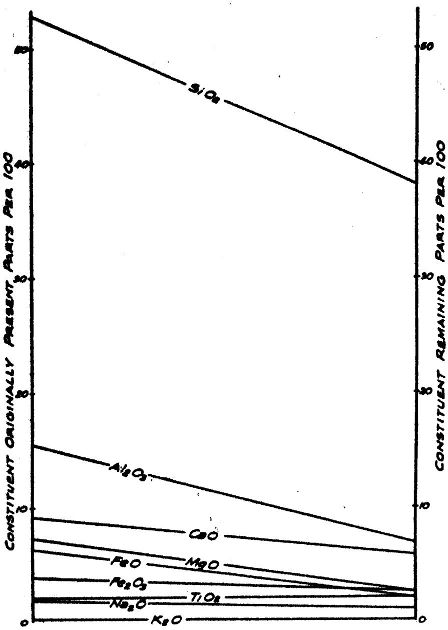

FIG. 7.—Comparison of changes produced by steam, air, and sulphur dioxide (Sample IV). TiO_2 is kept constant and the changes in other constituents compared with it.

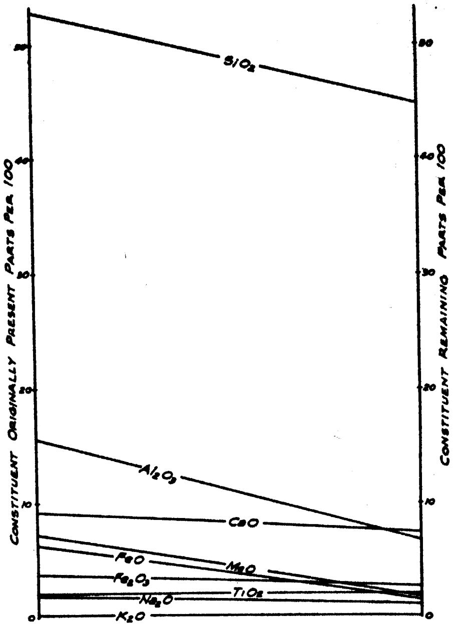

FIG. 8.—Comparison of changes produced by steam, air, carbon dioxide, and sulphur dioxide (Sample V). TiO_2 is kept constant and the changes in other constituents compared with it.

TABLE 10

ANALYSIS OF WHITE DEPOSIT

(In Percentages)

Constituent	Sample I	Sample II	Average
SiO_2	32.85	32.67	32.76
Al_2O_3	0+	0+	0+
Fe_2O_3	0.193	0.207	0.200
FeO	0+	0+	0+
MgO	0+	0+	0+
CaO	17.01	17.13	17.07
Na_2O	0+	0+	0+
K_2O	0+	0+	0+
$-H_2O$	13.66	13.55	13.60
TiO_2	0+	0+	0+
ZrO_2	0+	0+	0+
P_2O_5	0.016	0.018	0.017
SO_3	36.58	36.46	36.52
S	0+	0+	0+
Cr_2O_3	0+	0+	0+
MnO	0+	0+	0+
SrO	0+	0+	0+
BaO	0+	0+	0+
Total	....	....	100.17

at once that there is a considerable excess of acidic constituents over basic constituents. The microscopic examination proves the presence of gypsum. Assuming all the calcium is in the form of gypsum, there remains an excess of 12.15 per cent sulphur trioxide and 2.63 per cent water. There is no other basic element which can combine with the excess sulphur trioxide. It is apparent, therefore, that the silicon dioxide has taken up sulphur trioxide, as well as water of hydration. A similar mineral, but containing a much lower percentage of sulphur trioxide, known as "melanophlogite," is found in Sicily.

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THE METEORITIC IMPACT ORIGIN OF THE MOON'S SURFACE FEATURES

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ABSTRACT

The craters on the moon appear to have been formed by meteoritic impact rather than by volcanism. This mode of origin is suggested by their size, shape, distribution, associated features, and other considerations. Many of the aspects of lunar craters, such as their circular shape and the presence of central peaks, which have been considered as disproof of their impact origin, are the result of the crater's being formed by explosion rather than by percussion. Variation of the physiographic form of these craters, with increase in their size from small, cup-shaped pits to large, walled plains, is mainly due to modification and melting by superheated molten lava, generated by the impact in the case of the larger craters. Maria are probably extensive lava plains generated by the impact of bodies of asteroidal dimensions and were formed relatively late in lunar history, as is indicated by the physiographic youth of the superimposed post-maria craters. Aside from the shape of the craters and the maria, the small mass of the moon and its low internal pressure make volcanism unlikely in the lunar environment.

INTRODUCTION

When Galileo pointed the first telescope toward the moon in 1609, he became the first human to observe its mountains and craters. Since then, selenographers have observed, studied, and mapped the moon's surface in such painstaking detail that it has been said that the portion of the moon facing toward our planet is better known in many respects than any equivalent portion of the earth. Nevertheless, there is no general agreement concerning the origin of the features on the moon's surface. Most interpretations can be classified in two general categories: (1) that the features are the result of volcanism or some related type of internal magmatic activity and (2) that the features are the result of the impact of meteorites and related extra-lunar bodies with the moon's surface. Nearly all astronomy texts discuss both theories but favor volcanism, inasmuch as it appears to have a large majority of proponents. The present writer has, however, been impressed with the fact that all the major topographical forms on the moon, including the craters, the maria, and most of the mountains, can be explained most satisfactorily by the impact of extra-lunar bodies. In addition, volcanism and diastrophism do not seem to have played an important part in fashioning the features on the moon. Some evidence supporting this thesis is presented in this paper.

THE LUNAR ENVIRONMENT

The moon revolves around the sun at a velocity of 19 miles per second and around the earth at a velocity of about ½ mile per second in a slightly elliptical orbit and at an average distance of 239,000 miles. Therefore, a direct head-on lunar collision with a meteorite traveling at the solar parabolic velocity of 26½ miles per second would impinge at 45 miles per second, whereas the less common tail-end collision would strike at a velocity of about 8 miles per second. Relative to the earth, the moon completes one revolution and one rotation simultaneously in a period of 27⅓ days,

so that the moon always presents the same face toward the earth. Owing to actual and apparent librations of the moon, earth-dwellers see a total of 59 per cent of the moon's surface, the remaining 41 per cent being invisible.

The lunar diameter of 2,160 miles is about one-fourth that of the earth, so that the volume of the moon is one forty-ninth that of our planet. However, because the lunar specific gravity is only 3.3 while the specific gravity of the earth is 5.5, the total mass of the moon is only one eighty-first that of the earth. The total lunar surface area is $14\frac{1}{2}$ million square miles, or about $7\frac{1}{2}$ per cent that of the earth. The 59 per cent of the moon that the earth-dwellers can observe is, therefore, $8\frac{1}{2}$ million square miles, or approximately equivalent to the area of North America.

Because of the relatively small lunar mass, the force of gravity on the moon's surface is only one-sixth that of the force of gravity on the earth's surface. Thus, even heavy basic rocks, if such are present on the moon's surface, can be displaced and thrown about more readily that equal-sized blocks of pumice on the earth. Owing to the low lunar gravity, lunar features will have many times—possibly six times—the linear dimensions of features on the earth produced by equal forces.

Observations show that the moon does not have, and theoretical consideration suggests that the moon never has had, an atmosphere. The absence of an atmosphere eliminates nearly all the familiar terrestrial gradational forces, such as wind or water action. Nor can there be extensive oxidation or hydration or formation of sedimentary rocks. However, a popularly held impression that the moon is a completely changeless world is probably not justified, for examination of lunar features clearly shows them to be in various stages of erosion. In view of the absence of most of the usual erosional agents, erosion of the moon must be extremely slow and must be accomplished, for the most part, (1) by catastrophic action, including blast action, melting by lava and hot gases, moonquakes, and flying missiles, and (2) by insolation. The great variation in temperature on the moon's surface from above the boiling-point of water to about $-250°$ F. must have a slow, but nevertheless considerable, pulverizing effect on the outer few yards of the lunar lithosphere. In addition to the mechaniical disintegration, the expansion and contraction of rock produces a mass downgrade creep,[1] which slowly reduces the angle of slope of lunar surfaces. Given sufficient time, molecular flow or solifluction and "micro-isostatic" adjustments may also cause gradation.

CRATERS

GENERAL

The most conspicuous lunar features are the craters, of which over thirty thousand have been identified. Although these features are of a second order of magnitude as compared to the maria and the terrae,[2] the correct interpretation

[1] C. F. S. Sharpe, *Landslides and Related Phenomena* (New York: Columbia University Press, 1938), p. 28.

[2] For the purposes of this paper, the word "terra" (plural, "terrae") is used to refer to all the light-colored areas of the moon's surface, as contrasted with the dark areas or "maria" (singular, "mare"). The writer is unaware of any previous use of this term other than by Kepler, who wrote: "Do maculos esse maria, do lucidas esse terras." This statement is quoted by C. Fisher in *The Story of the Moon* (Garden City, N.Y.: Doubleday, Doran & Co., 1945), p. 104, as possibly originating the misnomer "maria" (Latin, "seas"), whereas the word "terra" has apparently never been commonly used. It is convenient to divide the terrae into four areas: (1)

of the craters holds the key to the origin of other lunar features. It is therefore desirable, first, to describe and analyze some of the aspects of lunar craters which, the writer believes, show that these features can be explained only as a result of the impact of extra-lunar bodies.

SIZE

The discernible lunar craters vary in size from small, lipped, cup-shaped pits less than a mile in diameter, which the telescope is barely able to resolve, to huge, walled plains, such as Calvius (142 miles in diameter, 20,000 feet deep). Between these two extremes there are medium-sized craters (Figs. 1–4), characterized by one or more central peaks, such as Theophilus (Fig. 1), 64 miles in diameter, 16,000 feet deep; Tycho (Fig. 2), 56 miles in diameter, 12,000 feet deep; and Copernicus (Fig. 4), 56 miles in diameter, 12,000 feet deep. Although the craters tend to develop different characteristics with variation in size, there are gradations between all types, suggesting that all have a similar origin. The small pits and the large, walled plains cannot be considered end-members of the crater family, since there are probably numerous small pits beyond the resolving power of the telescope and since, as the writer attempts to show below, the maria are probably to be considered large craters.

The large size of lunar craters has been cited as evidence that the forces which created the lunar landscape were of a much greater magnitude than any which the earth has experienced. However, because of the small force of the moon's gravity, one should divide the linear dimensions of lunar craters possibly by a factor of 6 when comparing them with terrestrial craters. Thus, some of the largest terrestrial calderas may be comparable to the large lunar craters. But, according to H. Williams,[3] all large calderas are primarily due to crustal collapse caused by the withdrawal of magmatic support. He states that volcanic explosion craters on the earth, unmodified by slumping, do not exceed 1 mile in diameter. Therefore, although the lunar craters are probably not larger than those that can be produced by volcanic forces, the proponent of lunar volcanism must postulate extensive subsidence or volcanic explosions of proportions unknown in geological experience to account for the large size of many lunar craters.

Although the size of a volcanic explosive crater is apparently limited, the size of an impact crater is dependent only upon the size of the impinging missile. One can predict, then, that impact craters will be of assorted sizes and will exhibit little tendency toward a "standard" or limiting size. Although the effect of the impact of such a high-velocity missile is imperfectly understood, there is sufficient evidence to show that a high-order explosion results.[4] Therefore, since the resulting crater is formed by explosion rather than by percussion, a relatively small meteorite can produce an enormous crater in the lunar environment. Boon and Albritton[5] have calculated that a body only 250 feet in diameter and with an impact velocity of about 19 miles per second contains suffi-

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Terra Australis, Southland, (2) Terra Orientalis, Eastland, (3) Terra Borealis, Northland, and (4) Terra Occidentalis, Westland.

[3] "The Caldera Problem," *Proc. Geol. Soc. Amer.*, *1937* (1938), p. 257.

[4] J. D. Boon and C. C. Albritton, Jr., "The Impact of Large Meteorites," *Field and Laboratory*, Vol. VI (1938), pp. 56–64; C. C. Wylie, "Meteoric Craters, Meteors, and Bullets," *Pop. Astr.*, Vol. XLII (1934), pp. 469–71.

[5] See ftn. 4.

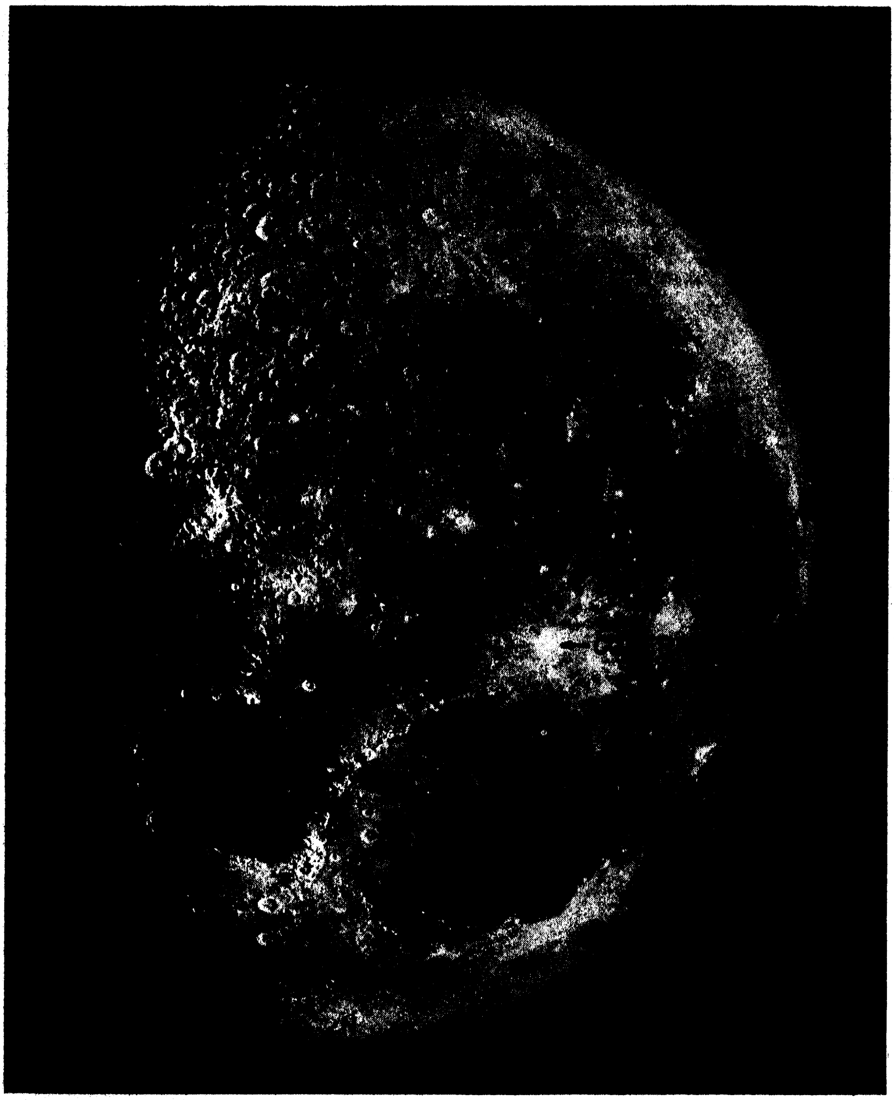

FIG. 1.—The moon, age 19 days. Photograph is oriented with south at the top, in accordance with astronomical convention. Photograph by Mount Wilson Observatory.

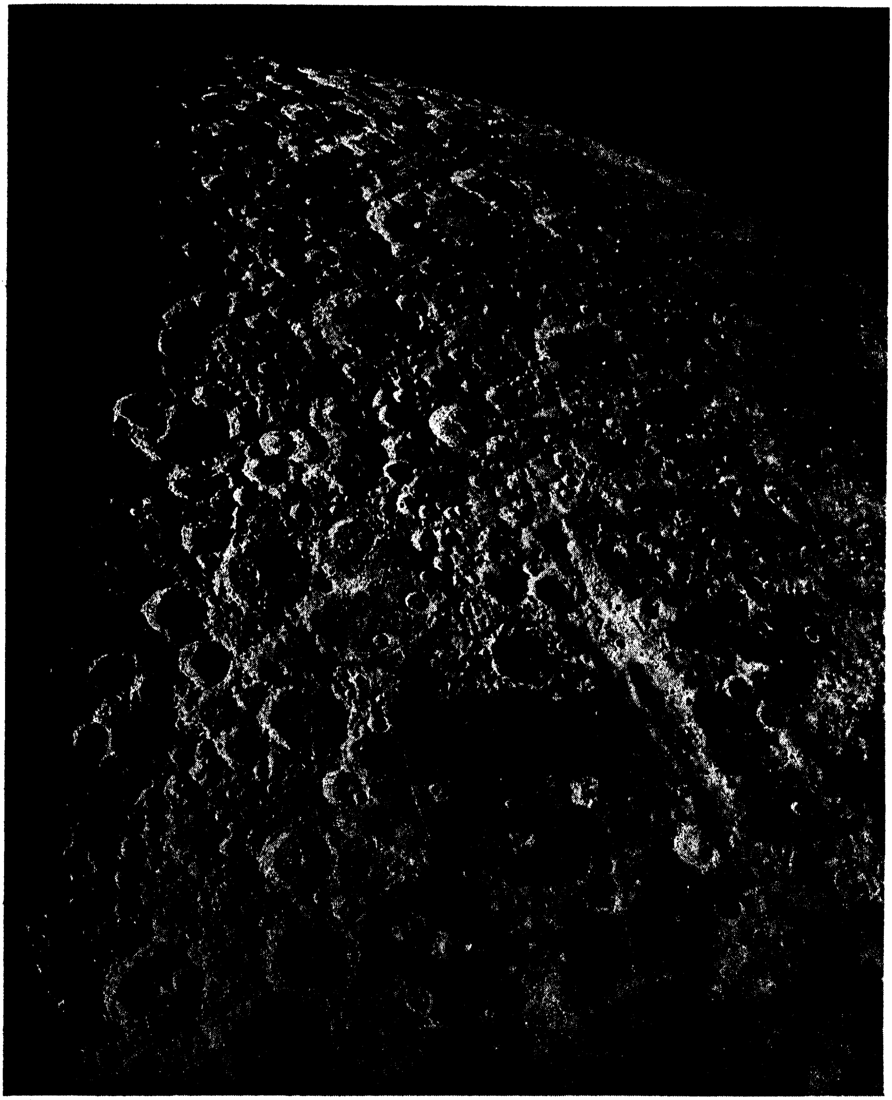

FIG. 2.—Southern portion of the moon, showing part of Mare Nubium and part of Terra Australis. Mare Nubium appears to be a thin lava plain only partially inundating an old terra surface. Youthful craters are superimposed on the mare, whereas youthful, mature, and old-age craters cover the terra. Note the linear arrangements of the craterlets marked *r*. Photograph by Mount Wilson Observatory.

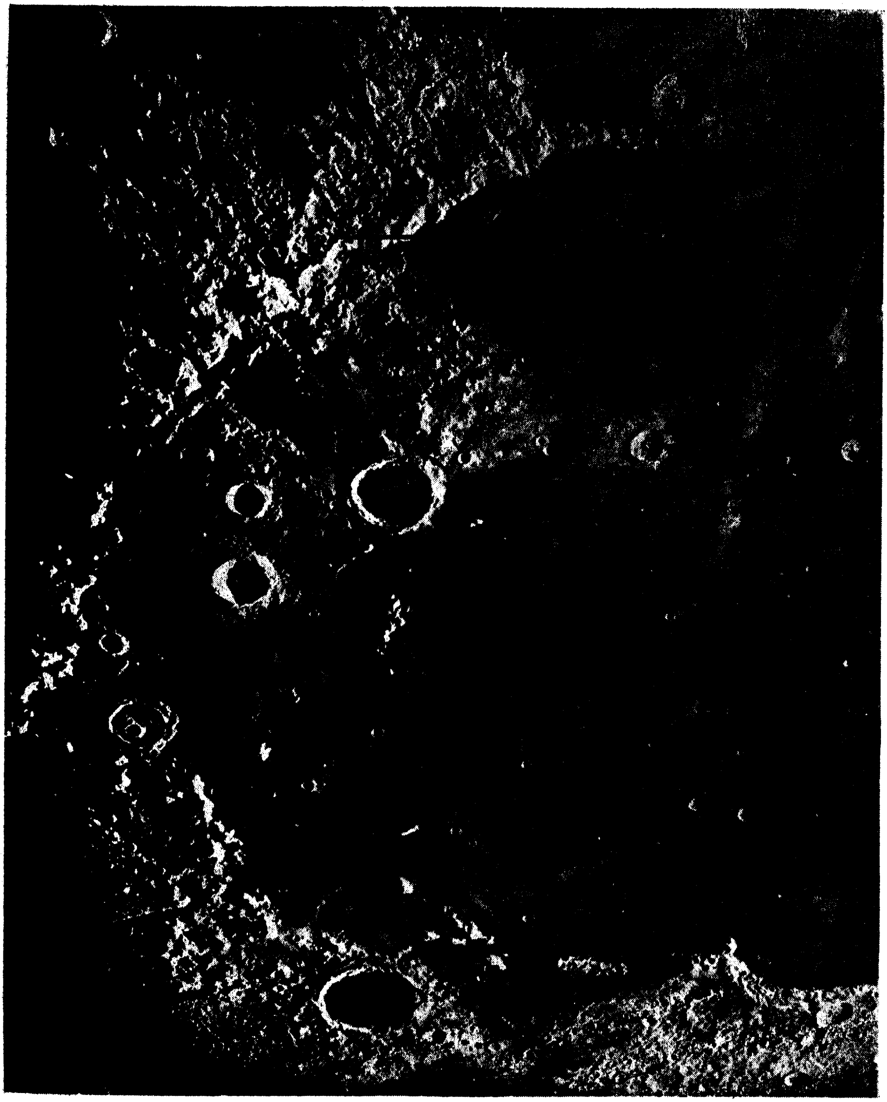

FIG. 3.—Mare Imbrium and vicinity. The lunar mountains surrounding Mare Imbrium appear to be masses of explosion-scoured rubble, with a few superimposed youthful craters formed after the Imbrium impact. Note the rill or crevice marked *1* and the winding maria ridges marked *2*. Photograph by Mount Wilson Observatory.

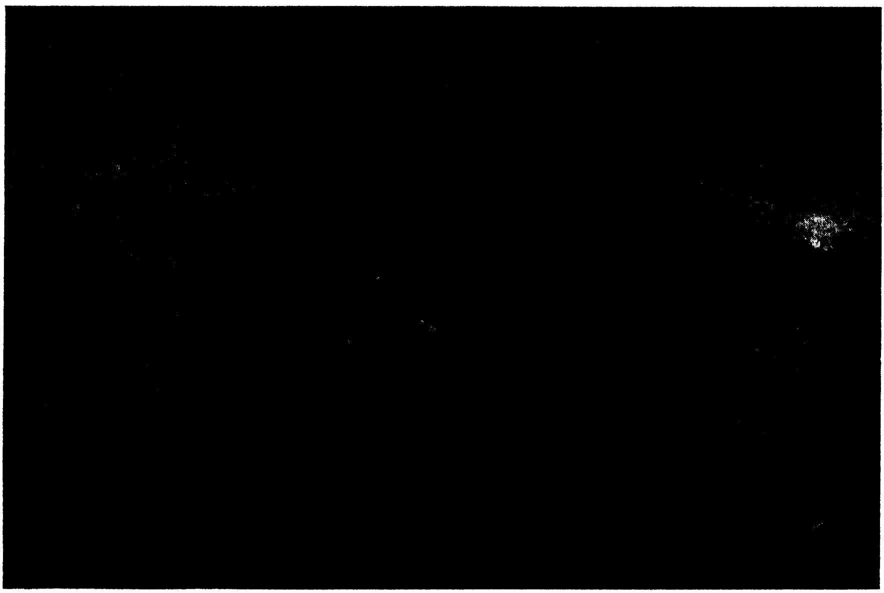

FIG. 4.—*Above:* Copernicus and vicinity. Copernicus is a youthful, medium-sized crater (56 miles in diameter, 12,000 feet deep), with a well-developed ray system. The chain of pits marked *B* are, for the most part, not true craters, as can be observed by comparing them with the crater marked *A*. Note that the Carpathian Mountains are explosion-grooved and that these grooves converge toward the center of Mare Imbrium. Photograph by Mount Wilson Observatory. *Below:* Meteor Crater, Arizona. A terrestrial meteoroid impact crater formed in recent times. This crater is similar in most respects to the smaller lunar craters. Aerial photograph by the writer in 1944.

cient energy to raise the mass of material ejected from Meteor Crater, Arizona, to a height of 65 miles. Although much of the energy is actually used in other ways, it is clear that a relatively small body, compared with the diameter of the crater formed, could have produced this terrestrial crater.

Perhaps the enormous amount of energy contained in a meteorite can be better appreciated by comparing it with a high-speed bullet. A bullet traveling at a velocity of $\frac{1}{2}$ mile per second produces a considerable amount of heat and semi-explosive effects upon impact. Yet, because the kinetic energy of a mass varies as the square of its velocity, a bullet traveling at the not uncommon meteoritic velocity of 40 miles per second would contain 6,400 times the amount of energy that it does at $\frac{1}{2}$ mile per second. C. C. Wylie[6] states that a meteorite traveling at such a velocity contains more than three hundred times as much energy as an equal volume of nitroglycerin.

The explosive nature of the impact of a high-velocity and chemically stable body, such as a meteorite, is not generally appreciated by earth-dwellers because our atmosphere burns up nearly all incoming meteorites and decelerates most of those not so destroyed to speeds of only a fraction of a mile per second. In contrast, a hypothetical moon-dweller would be aware of the explosive nature of meteorites but might doubt that a high-velocity and chemically stable body, such as a meteorite, can burn brilliantly because, in the atmosphereless lunar environment, one would never see a "shooting star" and all meteorites would explode on the lithosphere. Although such a moon-dweller would never see a stone burn, earth-dwellers have recorded meteorite explosions, because at infrequent intervals a giant meteoroid plunges through the atmosphere and strikes the surface with a velocity of many miles per second. Such a giant meteoroid, with a mass of at least a thousand tons or more has a relatively small surface compared to its mass, so that it is not greatly retarded by the friction of the air. The Siberian fall in 1908[7] was accompanied by an explosion of sufficient magnitude to devastate a wooded and swampy area 50 miles in diameter, although only a few small circular craters formed, the largest 50 meters in diameter.

SHAPE

Lunar craters do not closely resemble those produced by terrestrial volcanism, but they do resemble known terrestrial meteoroidal-impact craters, such as Meteor Crater, Arizona (Fig. 4). For example, in lunar craters: (1) the floors are depressed below the surrounding terrain; (2) the total volume of the material displaced and now present in the rims appears to be approximately equal to the volume of the cavity of the crater; (3) there are no unquestionable examples of associated lava flows; (4) they are not nested in mountain tops or other physiographic heights; (5) they have lipped rims; (6) they have a more or less constant depth-width ratio for a given type of crater; (7) the walls and rims of the craters are seldom breached; and (8) they have the appearance of being instantly and completely formed. This lack of similarity between lunar and terrestrial volcanic craters and calderas is appreciated by many who have sup-

[6] "On the Formation of Meteorite Craters," *Pop. Astr.*, Vol. XLI (1933), pp. 211–14.

[7] L. A. Kulik, "The Question of the Meteorite of June 30, 1908, in Central Siberia," *Pop. Astr.*, Vol. XLV (1937), pp. 561–62.

ported the hypothesis of lunar volcanism. They suggest that this may be due to peculiarities of the lunar environment. Yet there is nothing known about conditions on the moon which suggests that there might be such a great difference in shape between lunar and terrestrial features as there is in size. There are two shape characteristics of lunar craters: (1) their circularity and radial symmetry and (2) the central peaks, which have been frequently cited as evidence against the impact theory. These features are therefore selected for special analysis and interpretation.

Many selenographers have stated that the high radial symmetry and the circularity cannot be explained by impact, because few meteoroids would impinge normal to the moon's surface, while most would strike at oblique angles, producing oval craters. Early advocates of the impact theory attempted to account for the lack of oval craters by special postulates, such as having the angle of incidence controlled by lunar gravity or by having the oval craters spring back to a circular shape by elasticity. G. K. Gilbert[8] supposed that the missiles were part of a Saturn-like ring which revolved around the earth. On this basis he showed how a majority of the missiles would strike at a high angle of incidence. It is, however, unnecessary to postulate any special condition, because an explosion crater, in contrast to a percussion crater, has a circular shape and well-developed radial symmetry, regardless of the angle of incidence. Such an explosion crater may be somewhat modified by accompanying percussion effects; for example, a circular shape might be altered to a slightly oval shape and the radial symmetry altered to a slightly bilateral symmetry. Terrestrial craters, such as Meteor Crater in Arizona, the Siberian craters, the Estonian craters, the Wabar craters in Arabia, the Campo del Cielo craters in Argentina, the Henbury craters in Australia, and the Odessa crater in Texas, all of which are established as impact craters by the presence of associated meteoritic material, are quite circular in shape. Meteor Crater, Arizona, for example, is 3,800 × 4,000 feet, which is particularly significant, since there is evidence that the meteoroid approached at a low angle from the northwest.[9] All except a few of the thousands of meteorite fragments recovered have been found scattered around rather than in this crater, suggesting an explosion with almost complete destruction of the meteoroid. In contrast, terrestrial volcanic craters seldom exhibit the high symmetry and circularity apparent in lunar craters. Many volcanic explosions produce irregular-shaped cavities. Even calderas, such as Crater Lake, Oregon, which is considered to be a highly symmetrical caldera, is 6 miles long by 4 miles wide. Comparatively, volcanic explosions are probably of a low order, from a small area source, and in a series, so that the explosion cavities produced lack high symmetry.

Many lunar craters contain centrally located prominences, which, although never exceeding the outer rim in elevation, range up to over 5,000 feet in height. These prominences are most commonly present in the medium-sized craters, and they vary in shape from almost perfect domes to fluted pyramids and groups of separate, jagged peaks.

Although the mechanics of a meteorite-impact explosion and the resultant rock deformation are not well known, there is

[8] "The Moon's Face," *Bull. Phil. Soc. Wash.*, Vol. XII (1892), pp. 241–92.

[9] W. Goodacre, *The Moon* (Bournemouth, England: Pardy & Son, 1931), p. 29.

theoretical evidence to show that a crater with a central dome can be formed by such an explosion. A meteorite, when it strikes the moon's surface, is traveling many times faster than the shock waves it produces in rock, so that, initially, there is little pushing-aside of the material in front of the impinging body. Under this condition Boon and Albritton show[10] that, instead of deforming plastically, rock becomes highly compressed and then "backfires" elastically, with explosive violence. In this manner a damped-wave structure, consisting of a central dome with a surrounding ring graben, such as is characteristic of many lunar craters, might be produced by meteoroids, which would almost invariably strike at velocities greater than $2\frac{1}{2}$ miles per second, which is approximately the velocity of a shock wave in granite.

The lunar crater, Alpetragius (Fig. 2), 11,000 feet high, 26 miles in diameter, is an excellent example of a crater not modified by melting or erosion and therefore containing an almost perfect central dome. It is noteworthy that Alpetragius contains a dome rather than a cone, because, if this crater is an impact feature, a dome suggests a rebound structure, while a cone might suggest a huge "explosion cone" that had withstood the force of the explosion. The lack of a physiographically expressed dome in most of the smaller crater pits of the type to which Meteor Crater, Arizona, may be compared is possibly due to the small size and/or the low impact velocity of the impinging body. Although almost half of the medium-sized lunar craters contain central peaks, these prominences are rarely domical because sufficient superheated molten lava is generated to form a pool in the bottom of the crater and at least partially to melt the central dome and sap the outer wall. In this manner the central dome is undercut by melting, creating slides which modify its form to that of a fluted pyramid. If a large amount of molten lava is generated by the impact, as in the case of the large craters, the central dome may be reduced to a group of separate peaks or may be entirely destroyed, so that no indication of its ephemeral existence remains. Such an inner pool of lava also undercuts the outer wall, causing slides and slumps and producing the terraced or "wreath" structure exhibited by many craters, such as Copernicus. It is noteworthy that such craters as Alpetragius, which do not have their central dome modified by melting, also do not have a "wreathed" outer wall.

An objection to the above explanation for the central peaks is that there are no comparable terrestrial structures of proved impact origin. There are, however, many geological explosion structures characterized by a central uplift, which have been ascribed to deep-seated and "muffled" volcanic explosions[11] but which may actually have been produced by meteoritic impact.[12] Recently formed impact craters, such as Meteor Crater, Arizona, are probably not of sufficient size to exhibit a physiographically expressed dome.

Proponents of lunar volcanism might explain the central peaks as solidified plugs of lava pushed out of a volcano vent by subterranean pressure. For this

[10] J. D. Boon and C. C. Albritton, Jr., "Meteorite Scars in Ancient Rocks," *Field and Laboratory*, Vol. V (1937), pp. 53–64.

[11] W. H. Bucher, "Cryptovolcanic Structures in the United States," *16th Internat. Geol. Cong. Rept.* (1933), pp. 1066–70.

[12] J. D. Boon and C. C. Albritton, Jr., "Meteorite Craters and Their Possible Relationships to 'Cryptovolcanic Structures,'" *Field and Laboratory*, Vol. V (1936), pp. 1–9.

type of phenomenon there is a well-known geological precedent. Mount Pelée in Martinique thrust up above the top of the crater an obelisk-like spine to a height of over 1,000 feet, but this was soon destroyed by crumbling. A second possibility is that these central prominences are parasitic cones. Third, certain domes, such as the dome in Alpetragius, might be laccolithic in nature. Fourth, these central cones might be formed by crypto-volcanism, i.e., a deep-seated "muffled" explosion of gases derived from magmas. Such an explosion might be too weak and unconcentrated to blow out a crater but sufficiently strong to dome the surface rocks. Yet, any hypothesis involving volcanism does not adequately explain (1) why these peaks are invariably located in craters and in the central position and (2) why the crest of such a peak is invariably well below the rim height. Also, these various hypotheses involve rather complicated, and in some cases illogical, sequences of events.

As evidence for lunar volcanism, some selenographers have stated that a few of these central peaks contain craterlets nested in their summits.[13] The present writer has not been able to identify any unquestionable examples of such hilltop craterlets. A few craters, such as Timocharis, under the condition of lighting in Figure 3, appear to contain such a hilltop craterlet. Yet, if one examines a photograph of this same feature with the light falling from the opposite direction,[14] no craterlet is seen, so that the supposed crater may be the shadow cast by an isolated peak. Certain other central prominences appear to have a group of isolated peaks with a saddle or possibly a slight depression or "pseudo-crater," which might be misinterpreted as a true crater. The absence of these hilltop craterlets is obviously predicted by the impact theory, except for the occasional chance hit of a second small meteorite on the top of a central prominence. However, if the proponent of lunar volcanism claims that true hilltop craterlets are common, he should explain how they were formed, because other types of lunar craters are not nested in peaks, as is the habit of terrestrial volcanic craters.

DISTRIBUTION

Lunar craters are many times more abundant on the terrae than on the maria because, as is shown below, the maria were formed relatively late in lunar history. If one allows for this fact, it is apparent that the craters are scattered at random. Such a scattered distribution is in accord with the impact theory, since the point at which a meteorite strikes the moon's surface is controlled largely by random probability. Volcanic features, on the other hand, should be developed along fault lines or other lines of tectonic weakness. The lack of any apparent tendency of the great majority of craters to show any linear arrangement is, therefore, significant evidence against lunar volcanism.

There are a few examples of linear arrangement of small crater-like pits, such as those in the vicinity of Copernicus, which are too well oriented to be the result of random impact (Fig. 4). The pits near Copernicus are not of impact origin, for they differ markedly from typical craters of similar size in that (1) they are not lipped and (2) they are oval and elongated, grading into trench-shaped grooves. Among these

[13] See ftn. 9.

[14] N. S. Shaler, "A Comparison of the Features of the Earth and the Moon," *Smithsonian Contr. to Knowledge*, Vol. XXXIV (1903), Pl. XXI.

pits there are a few true craters which can readily be identified by their symmetry or by examining this area on a photograph with "overhead" lighting, in which case the true craters show up as white spots and the pits disappear. One possible explanation of the pits is that they are the result of collapse of a lava tunnel or similar subterranean void formed by contraction as the subsurface lava of the maria cooled after the outer skin of lava had solidified. Also, there may be some relation of these pits to the serpentine ridge which extends from this region northward into Mare Imbrium. The formation of these pits may have been caused by collapse following the moonquake associated with the explosive formation of Copernicus.

There are a few linear chains of small true craters on Terra Australis, such as a row extending to the west from the south rim of the crater Ptolemaeus (Fig. 2). Such a line of small craters might be explained by the impact of a meteorite traveling tangentially to the moon's surface. Upon initial grazing contact, such a body might shear into a number of fragments, each of which would then impinge and explode separately. An alternate possibility is that such a string of craters was formed by a group of meteors, traveling in a swarm as in a comet's head, which impinged tangentially.

PHYSIOGRAPHIC AGE OF LUNAR CRATERS

An examination of the lunar surface shows that different craters are in various stages of erosion. In fact, the terms "youthful," "mature," and "old-age" may be conveniently applied to these craters in much the same manner as they are applied to terrestrial physiographic features. Craters of the same physiographic age were not necessarily formed contemporaneously, for some may have passed through the stages more rapidly than others.

Youthful craters, such as Copernicus and Tycho, have (1) high angles of slope, (2) few superimposed craters, (3) unscarred walls, and (4) sharp outlines. Craters in early youth may be readily identified both on the maria and on the terrae when examined under conditions of "overhead" lighting, for the large craters in early youth are marked by a ray system, while the small craters are marked by a bright halo, often exhibiting "asterism," i.e., a miniature ray system. Youthful craters are present on the maria and on the terrae in about equal numbers.

Mature craters are most common and are largely confined to the terrae. Mature craters are characterized by (1) a moderate angle of slope, (2) a moderate number of superimposed craters, (3) a moderately sharp outline, and (4) a moderately scarred appearance. Clavius (Fig. 2) is an excellent example of such a mature crater.

Old age craters, such as Regiomontanus and the large unnamed walled plain immediately to the southeast (Fig. 2), are confined to the terrae or are formed by inundation by maria lava. These craters are typified by (1) a low angle of slope, (2) many superimposed craters or lava inundation, (3) an indistinct outline, and (4) a highly scarred appearance.

A popular version of the volcanic theory is that all the lunar craters were formed many eras ago by some type of bubbling or widespread volcanism when the moon was in a semimolten state, so that the present surface of the moon is the original crust. Yet the youthfulness of some craters, such as Tycho, suggests that they have been formed in relatively recent geological time, probably in the

Cenozoic. As lunar erosion is extremely slow, the elapsed time between the formation of the youngest and the oldest craters may be one or more geologic eras. It is likely that crater formation has been a continuous process, which is still taking place at infrequent intervals when large meteorites strike the moon. If the moon did cool from a molten state, the original crust probably has been so altered by later crater formation that, as is the case with the earth, an original crust is nowhere exposed.

CRATER RAYS

Radiating from the most youthful craters are light-colored streaks or rays, which are best displayed under high incidence of sunlight. These rays are well displayed by such craters as Copernicus, Kepler, Byrgius, Anaxagoras, Olbers, Aristarchus, and Tycho. Some of the streaks extend to distances of almost 2,000 miles from the craters. As the rays cast no shadows and as they pass indiscriminately and without interruption over all terrain features, they are apparently thin surficial deposits of material blasted out of the lunar craters from which they radiate. Corresponding to the large ray systems are bright halos of small youthful crater pits, which display some "asterism," forming a miniature ray system. Owing to the low force of lunar gravity, the lack of an atmosphere, and the high curvature of the moon's surface, the great length of the rays can be accounted for by ejection velocities of only a fraction of a mile per second, because ejected fragments will travel from twenty-five to forty times as far on the moon as on the earth. Although the rays indicate an explosive origin for the lunar craters, ejection velocities, produced either by volcanism or by meteorite impact, would probably be sufficiently great to account for the rays.

As the lunar rays are associated with all the most youthful craters, probably all originally possessed a ray system, which, with the passage of time, was covered with rock or cosmic dust, or destroyed in some other manner. The nature of the highly reflecting material forming the rays is problematical, but it may be finely pulverized rock, meteoritic fragments, and solidified, recrystallized, or glassy material ejected in the molten state. Perhaps tektites are such material which was ejected at a velocity greater than $1\frac{1}{2}$ miles per second, so that it left the moon's gravitational sphere and fell to the earth. Tektites contain lechatelierite or fused quartz, which requires too high a formation temperature to be a product of volcanism, although such material is produced by meteorite impacts.

MARIA

The dark-gray lunar plains or maria, nearly all of which are interconnected, cover about one-half of the visible surface of the moon. If maria are present on the far side of the moon, they are not connected with those visible to the terrestrial observer, for the well-developed maria do not extend beyond the limb. These dark-gray plains lie at topographically lower levels than the terrae, so that, if a hypothetical hydrosphere were poured upon the moon, the water would cover at least a large part of the maria surfaces before beginning to inundate the terrae. Although there is no general agreement concerning the origin of these dark-gray plains, they have been almost universally interpreted as extensive solidified lava fields. The surfaces of the maria are relatively smooth and featureless and are sprinkled with comparative-

ly few craters; with numerous long, narrow crevices or rills; and with long, winding ridges of low relief. Inasmuch as the opposing walls of the rills show no evidence of vertical offset or of horizontal displacement, these features are probably not faults but possibly are crevices produced by contraction accompanying the cooling of the lava. A probable explanation for the long, narrow, winding, and branching ridges is that they are pressure ridges formed in the later stages of the cooling of the maria by the movements of subsurface fluid lava after the surface had cooled to a viscous or semisolid state. Inasmuch as the superimposed craters are all youthful and the maria inundate the physiographic features of the terrae both along the "shores" and in the central areas of some maria, such as Mare Nubium, it is apparent that the maria were formed late in lunar history.

The lava of the maria was apparently originally heated well above the temperature necessary to melt the rock of which the lava is composed. This superheated condition is evident, since the lava melted many of the features of the terrae with which it came in contact and since it was highly fluid, for it spread out over large areas, forming smooth plains. The formation of a superheated lava can be readily accounted for only by the impact of a large meteorite which would contain sufficient kinetic energy to change a large mass of solid rock almost instantaneously to superheated molten lava. In contrast, volcanic lava characteristically remains at relatively low temperatures near the solidifying point and is, therefore, incapable of accomplishing a significant amount of melting of the surface rocks with which it comes in contact. Such low temperatures are normal, since volcanic lava is not formed instantaneously but rather slowly in a subterranean reservoir, where stoping and melting of the walls of the reservoir prevent superheating.

If one accepts the impact origin of the lunar craters as presented above, the impact origin of the maria follows logically, for there is no great difference between some of the larger lunar craters, such as Calvius and Schickard, and some of the smaller maria, such as Mare Crisium. Of course, the meteoroids that formed the maria must have been extermely large, probably having asteroidal dimensions of many tens of miles. Although the maria retain only such characteristics of the craters as circularity and a depressed floor, the difference between the maria and the large craters becomes understandable if one extends one step further the changing aspects of the crater family beyond the large walled plain. In the crater series the variation of form with size is probably primarily due to the increasingly important role played by the molten rock, formed upon impact. Thus, small crater pits are unmodified by melting, and the medium-sized craters are only moderately modified by melting, whereas the formation of the large walled plains was accompanied by sufficient melting to destroy the central peak, wreath the outer wall, and partially fill the crater with a lava pool, decreasing the depth-width ratio. It is not surprising, therefore, that the primary effect of the impact of a meteoroid much larger than that which produced the walled plains is the generation of a large quantity of extremely hot lava. In fact, in the formation of the maria, sufficient lava has been generated to destroy or submerge the central dome and to breach and partially destroy the

surrounding wall, thereby flowing out over other parts of the lunar surface.

The most convincing evidence of the impact origin of the maria is found in Mare Imbrium (Fig. 3), a nearly circular area about 750 miles in maximum diameter, with a surface area of about half-a-million square miles. Mare Imbrium is bounded on three sides by mountain ranges, which have peaks ranging from 5,000 to 20,000 feet, named, beginning with the range immediately north of Copernicus, the lunar Carpathians, the lunar Apennines, the lunar Caucasus, and the lunar Alps. One encounters difficulty in attempting to explain these ranges by any process of mountain formation used to explain terrestrial mountains. The general shape of these features precludes the possibility that they were formed by folding, by volcanism, or by erosion. It has been suggested that these ranges are tilted fault-blocks and that the steep fronts facing the maria are fault scarps,[15] but according to such an explanation one would expect the dip slope to be a mature or old age surface, covered with numerous craters and other features. Actually, the dip slope appears to be a mass of rubble, with a few superimposed youthful craters, formed later than the mountains. Useful for comparison are the lunar Altai Mountains (Fig. 1), which appear to have formed by foundering along a fault zone. The terrain on both sides of the Altai scarp is an old age surface.

A reasonable explanation for the mountain ranges around Mare Imbrium is that they are of catastrophic origin and originated in a manner comparable to the ring mountains of the craters, by the impact explosion that formed Mare Imbrium. These mountains without "roots" originally may have encircled the maria more completely before they were partially destroyed by melting. They appear to be superimposed upon a structural ring arch, which forms a semicircle around Mare Imbrium (Fig. 3). This ring arch is physiographically evident because it is followed by a ring syncline into which lava has flowed, forming maria regions. These ring structures may be outer rings of the "damped-wave" impact structure associated with a meteorite impact.[16]

The vast amount of lava generated by the Imbrium impact, and possibly added to by lava released from the moon's interior, was apparently sufficient to breach the walls of the maria, so that it flowed out over other parts of the lunar surface, inundating the terrae and resurfacing some of the older maria scars. Mare Nubium, in particular, appears to have been formed by inflowing lava, because this region is not circular in shape and has only a thin skin of lava that partially covers the underlying terra surface. The excellently developed ray systems in this region may be explained by postmaria impacts, which have pierced the thin lava skin and exploded in the underlying and lighter-colored terra.

Further proof of the explosive origin of Mare Imbrium is in the lunar valleys and the "grooves" or "striations" which diverge from the center of this mare for many hundreds of miles. These valleys are well developed in the lunar mountains surrounding Mare Imbrium, while the "striations" and "grooves," although everywhere present around the mare, can be best seen in the central part of the moon (Fig. 1). These features cannot be faults, for in many cases they pierce both

[15] R. T. Chamberlin, "The Moon's Lack of Folded Ranges," *Jour. Geol.*, Vol. LIII, No. 6 (1945), pp. 361–73.

[16] See ftn. 10.

the northeast and the southwest rims of a crater without disturbing its bottom; therefore, these features must be surficial scars, probably formed by large missiles exploded out of Mare Imbrium. Because of the pulverized nature and the light weight of lunar rocks, these missiles had sufficient cohesive strength to plow and furrow the surface. There is evidence that these "striations" are not of meteoritic origin, for the missiles which formed them had a velocity low enough to produce percussion, rather than explosion, features.

Certain other maria, such as Mare Serentatis and Mare Crisium, have circular shapes and probably a thick layer of lava, suggesting that they are also impact scars rather than formed of lava from the Imbrium impact. Since all the maria surfaces are of approximately the same physiographic age, the maria must be approximately contemporaneous in origin, or the maria surfaces must have been reflooded with a new layer of lava from Mare Imbrium. The lack of a mountain ring of detritus around these other maria and the fact that the "shores" of these maria inundate old age terrae surfaces may be accounted for by complete destruction of such a mountain ring soon after formation by the lava of the maria. Since the centers of Mare Imbrium, Mare Serentatis, and Mare Crisium form a straight line, trending east to west, there may have been a triple impact of the Mare Imbrium body and two secondary "satellites," all three revolving in the plane of the ecliptic. The remaining maria can be largely accounted for by overflow of lava from these three maria.

VOLCANISM AND LUNAR ENVIRONMENT

Aside from the lack of volcanic features in the present moonscape, the moon's surface lacks features resulting from the large-scale folding, faulting, and intrusive activity which indicate crustal instability and usually accompany volcanism. A consideration of lunar "geophysics" suggests that extensive volcanism is not likely on the moon and similar small celestial bodies except in the early youth of a body cooling from a molten mass.

The lunar surface lacks large-scale folding, although orogenic folding should be plainly visible if present. There is some evidence of ring arching associated with Mare Imbrium, and there was some folding associated with crater formation; but there is no counterpart of terrestrial geosynclines, geanticlines, or folded ranges. The only clearly apparent folded features on the moon are the ridges on the maria, which are, presumably, formed by lava flowage rather than by internal compressive stresses. If compressive forces acted on the moon's surface with the equivalent force and effect with which they have acted on the earth's surface, one might expect folded lunar mountains many times higher than terrestrial mountains because of the low lunar gravity and the slowness of erosion. Perhaps folding is not to be expected on the moon, for it is normally produced below the surface under high compressional loads. Such folding is not evident until the folded area is uplifted and exposed by erosion. Since lunar rocks have a low weight, one may predict that the lunar zone of fracture, in which faulting tends to dominate over folding, would be about ten times as thick as that of the earth.

The moonscape is probably highly shattered and complexly faulted, because there must be many faults produced by the explosions which formed the craters and the maria, including ring

faulting, ring landslip faulting, and radial faulting. However, although small forces would produce large displacements on the moon, there is no evidence of large master-faults or shear zones, such as are present on the earth. The rills and the valleys are probably not of fault origin. The lunar feature named the Straight Wall (Fig. 2), 70 miles long, 500–1,000 feet high, is, however, one unquestionable example of a lunar fault. Such a fault is not necessarily produced by internal stresses, since it can result from moonquakes accompanying meteoritic impacts. The scarp which forms the west-facing wall of the Altai Mountains may possibly be a fault scarp, although the nature of this scarp is problematical. Altogether, there is little evidence of folding or faulting of a nature to indicate internal instability, such as might be directly or indirectly associated with volcanism.

An examination of the moonscape also fails to reveal any evidence of intrusive igneous activity, although such activity is almost invariably associated with volcanism. For example, there are few features on the moon which can be interpreted as batholiths, stocks, laccoliths, sills, or dikes. The high symmetry of the lunar craters indicates the homogeneous nature of the lunar surface and suggests the absence of buried intrusive bodies.

It is necessary to tread on unknown ground even to hazard a guess about the past or the present internal condition of the moon; for this requires a knowledge of the age of the moon as a celestial body and a knowledge as to whether it cooled from a molten state, grew by cold accretion, or was torn from the earth. However, a small celestial body, such as the moon, would cool internally and probably become inactive diastrophically in a small fraction of the time required for a larger celestial body, such as the earth; therefore, if the moon is even of a moderate age compared to the earth, it is probably internally cold and inactive. Yet many lunar craters are physiographically in early youth, indicating that they are of geologically recent age.

Although the absence of a lunar hydrosphere does not make volcanism impossible, this lack of water other than juvenile is unfavorable to the formation of volcanic explosive features, since water serves as a flux which lowers the temperature at which rocks liquefy and is the primary explosive agent of volcanism.

Planets of the solar system furnish evidence that the strength of the crust of a celestial body has an inverse relation to the mass. Therefore, it can be predicted that our satellite, because of its small mass and low specific gravity, has a strong crust and is not subject to such plastic deformation as is the earth. Also, owing to the mass and specific gravity of the moon, the internal pressure at its center is equivalent to the pressure at a depth of only about 100 miles in the earth's crust. Both of these conditions are unfavorable to the development of volcanism.

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LATE-GLACIAL AND POSTGLACIAL CHRONOLOGY ON ADAK

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ABSTRACT

A late-glacial and postglacial chronology on Adak Island in the Aleutian chain is represented by a series of three wind-blown sands, each terminated by a soil zone, and all three overlying a slightly weathered late-glacial till and marine terrace. Evidence of human occupation is present in the soil zones of the two upper sands. The younger culture is recent Aleut, the older is unidentified. It is suspected that the chronology results from variations in climate obtaining over a large portion of the North Pacific.

INTRODUCTION

The island of Adak is situated midway along the Aleutian chain and is one of the Andreanof group (see Fig. 1). It is a mountainous island of approximately 275 square miles, with deep bays and re-entrants which give its coastline a length of about 2,000 miles. It is 28 miles long in a NNE-SSW direction and has a maximum width of 18 miles. The highest summits are Mount Moffett, at the northern end of the island, and an unnamed height in the southwestern portion of the island, with altitudes of 3,876 feet and 2,249 feet, respectively. The island is composed of intrusive and extrusive igneous rocks. Volcanism has progressed from south to north on Adak, a process noted as characteristic of many of the Aleutian Islands.[1] Mount Moffett and Mount Adagadak, both extinct volcanoes, represent the latest and most northerly expressions of this activity on Adak. Glaciers once existed on the island. Although the higher peaks and ridges were probably ice free during maximum glaciation, alpine glaciers united to form piedmont glaciers, which covered a large portion of the island.

The northern part of the island, with which this report deals, is essentially a peninsula (Fig. 1). Mount Moffett forms its northwestern extremity and is connected to the main portion of the island to the south by a ridge averaging 400 feet in altitude but reaching a little over 600 feet at two points. Mount Adagadak, with an altitude of 2,115 feet, forms the northernmost headland and is nearly cut off from the rest of the island by a lowland, much of which is occupied by Clam and Andrew lagoons.

The investigations here recorded are concerned with the wind-blown sands which have collected behind the beaches of Kuluk Bay and in the vicinity of Clam Lagoon, as shown in Figure 1. They were made during 1944, while the author was serving with the United States Navy.

WINDS AND SOURCE OF SANDS

Aerial photographs taken during the occupation of Adak by the armed forces of the United States indicate that the most recent dune pattern along the western shore of Kuluk Bay has resulted from winds moving from the northeast and east. The winds now eroding the Clam Lagoon dunes are also predominately from the northeast quadrant, although cutting is also accomplished by winds from the southwest.

Sands in the dunes consist chiefly of

[1] S. R. Capps. "Notes on the Geology of the Alaskan Peninsula and Aleutian Islands," *U.S. Geol. Surv., Bull. 857-D* (1934), p. 145.

feldspar and ferromagnesium minerals derived by wave or glacial action from the local bedrock. Comparatively little quartz is present. The sand has been blown inland from the beaches and deposited along the low coastal area fringing the northwestern portion of the island. As the winds moved southward and westward up into the hilly country of the island or spent their energy within the Kuluk Bay area, which is surrounded by high country on almost all sides, sand was deposited. Obviously, migration inland from the beach would be promoted by strong northeast winds, large supplies of sand, and decreased obstruction by vegetation.

CLIMATE

Weather records in the Aleutians are scattered and incomplete. Adak and the other islands in the chain enjoy a mild, temperate climate with abundant rainfall and relatively mild summers and winters. Although the available records on Adak cover only parts of two years, the island's weather appears to duplicate that to both the east and the west along the chain. The mean annual temperature is 39.7° F. The maximum mean annual temperature is 43° F. and minimum, 36.4° F. A full-year precipitation record is not available, but the annual precipitation probably approaches 60 inches. The prevailing winds are from the southwest and average 15 m.p.h. During the months of November, December, January, March, May, and June, however, prevailing winds are from the north and northeast.

VEGETATION

The vegetation of Adak has not been adequately studied and described. However, the writer's observations indicate that the island supports two general types of vegetation. The first is restricted to sand-dune areas near the shore. The second, which is by far the most extensive, covers the upland areas. No trees are indigenous to Adak or to the other Aleutian Islands.

The present surface of the dunes is covered with a hearty, well-rooted vegetation consisting of grasses, wild grains,

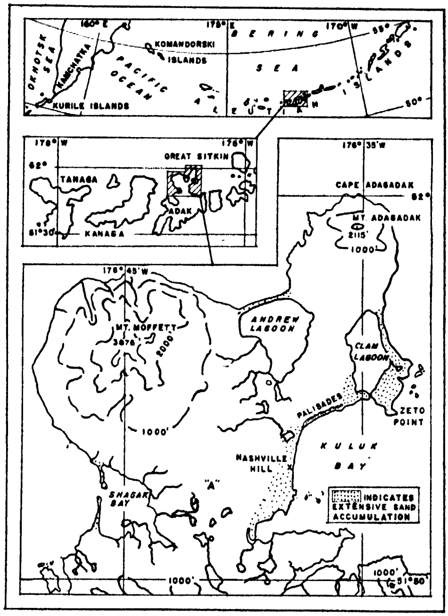

FIG. 1.—Index map

tuberous-rooted plants, and numerous species of flowers. The uplands are characterized by what may be termed a "dry tundra." This association includes large amounts of heather, blueberry, and grasses, with occasional ground willow, and a great variety of flowers which bloom in profusion during the short summers.

Thin deposits of sand, on slopes inland from the extensive dune accumulation along the beaches, indicate that the area was not bare of vegetation during periods

of sand accumulation. Sand was deposited in spite of a vegetative cover and in a form at least partially modified by it.

OTHER AREAS OF SAND ACCUMULATION

The Adak sands are not unique since areas of stabilized dunes are known to exist on other islands of the Aleutian chain. To the west of the Aleutians similar deposits are located in the northern Kurile Islands and on southern Kamchatka. The dunes are for the most part stable. In those places where erosion is now proceeding the process can usually be ascribed to man's activity. In a few instances instability can be attributed to strong wind and wave action. Aerial photographs reveal that in many places the abandoned villages of the recent Aleut or closely contemporaneous peoples are located in areas of stable dunes.

DESCRIPTION OF DEPOSITS OF WIND-BLOWN SANDS

The best single exposure in the sand-dune area of Adak is an 80-foot cliff of sand, till, and weathered bedrock on the northwest shore of Kuluk Bay where the sand dunes and the beach give way to the bedrock of the Palisades (Fig. 2). Brecciated bedrock, perhaps largely frost-riven, grades upward into 10 to 15 feet of bedrock in which the minerals are chemically decomposed. This is unconformably overlain by 4 to 5 feet of fresh gray till, slightly weathered at its upper limit. Over this lies the reddish soil of the oldest wind-blown sand. The soil carries stringers of white pumice, characterized by pellets averaging approximately $\frac{1}{4}$ inch in diameter. The pellets are composed of finely vesicular glass with small crystals of hornblende, small fragments of plagioclase (labradorite), and some biotite. There follows a second wind-blown sand, capped by its soil zone and overlain in turn by a third layer of wind-blown sand and soil zone. This last soil is the present surface of the stabilized dunes. The thickness of the section from brecciated bedrock to the ground surface is approximately 35 to 40 feet. The lower 40 feet of the 80-foot cliff is obscured by slump. Immediately to the south, till and bedrock are no longer exposed, and the three sands and their soils occupy a section of nearly 75 feet from beach to modern soil. The lowest sand and soil can be followed to the south for about 300 feet while the upper sands crop out almost uninterruptedly for $\frac{1}{2}$ mile in the same direction.

Aside from stratigraphic relationships, there is no apparent field distinction between the three wind-blown sands in their unweathered state. All are gray in color and of uniform consistency.

The thickness of each of the three soils ranges from 2 to 5 feet. They are all sharply defined at their upper limit and all grade downward into the sand from which they were formed. They differ, however, in their development. The two lower soils are marked by a "B" zone consisting of an accumulation of iron oxide which gives the sand a red color. This accumulation in the lowest soil is so great and cements the sand grains so completely as to form local bodies of "ironstone." The "A" zone, where present, is characterized by small amounts of humic material. The formation of both the lower soils was interrupted by the addition of small amounts of blown sand to the surface. The topmost sand is immature in comparison with the other two. Little iron oxide has accumulated in the "B" horizon, and the "A" horizon is made up of gray humic beds with intervening stringers of light-colored sand blown in during the process of soil formation. Volcanic ash further aids in dis-

tinguishing among the soils. The lowest soil carries lenses of pumice, and the youngest includes stringers of yellowish silt of high volcanic-ash content. No ash was noted in the middle soil.

Midway along the western shore of Kuluk Bay, a mile south of the above-described exposure, the sands are again well exposed. Here the sands have accumulated around the western and northern flanks of Nashville Hill, a plug of porphyritic granodiorite. The till is missing, and the sand series rests on beach deposits which form a marine terrace approximately 10 feet above high-water mark. The soil of the lowest sand, carrying the stringers of pumice, is discontinuous, but the middle and upper sands with accompanying soils are well exposed, as shown diagrammatically in Figure 3. The photograph of Figure 4 shows the soil of the middle sand overlain by the most recent sand and its soil zone. Higher on the slopes of Nashville Hill the sand cover on bedrock thins, and in road cuts the entire sequence of three sands and corresponding soils is only 5 feet thick. The relationships of the beach dunes, elevated beach deposits, and the sequence on the slopes of Nashville Hill are shown in Figure 5.

On the south side of Clam Lagoon, at the north side of Kuluk Bay, an extensive sand-dune area is now undergoing rapid wind erosion. The erosion of the Clam Lagoon dunes is believed to have commenced prior to the occupation of Adak by military forces in 1942. Sand is being deposited in Kuluk Bay, and considerable shoals already exist. In the "blowouts" the soil zone of the second or middle sand has been truncated. The photograph reproduced in Figure 6 shows a pattern, roughly that of a figure eight, resulting from the removal of the upper sand and the beveling of the middle sand and soil. Figure 7 shows the trace of the soil zone of the middle sand along a cut in the dunes, with the youngest sand on top and the middle sand below. At this place the lowest sand and soil were not identified nor was any till found. There is, however, a low terrace around the western and southern sides of Clam Lagoon. Its surface is approximately 10 feet above high water, and the sand deposits appear to rest on it. It is correlative with the elevated and sand-

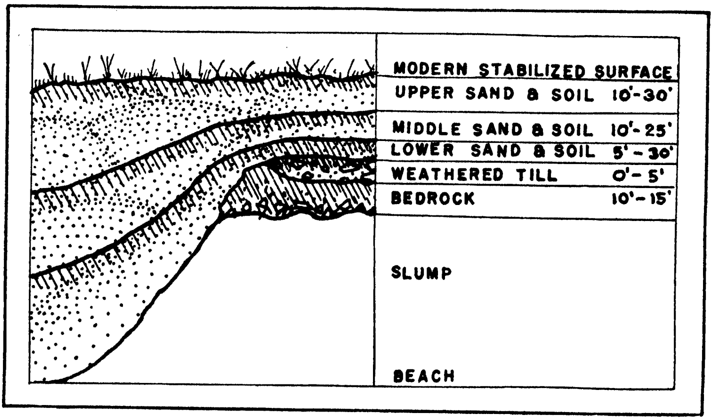

FIG. 2.—Generalized section at west end of Palisades

covered beach gravels noted at Nashville Hill. Its surface was formed at a slightly higher stand of sea-level and before the bar connecting Zeto Point with Mount Adagadak was built to form the eastern shore of the lagoon.

The till and sand-soil sequence is also developed away from the beach dune area in the hills of the northern part of the island. Near the Shagak Bay–Kuluk Bay divide and between the mountainous country to the south and Mount Moffett to the north (Point *A*, Fig. 1), overburden in a quarry cut illustrates the sequence. Above deeply weathered bedrock the section is approximately 5 feet thick. Till 12 to 18 inches thick is slightly weathered at its upper limit. The till is followed by some 12 inches of sand and silt in the top of which is developed a soil covered by a thin bed of pellet ash. Sand, silt, and clay, a foot thick, merge upward into discontinuous humic beds, also capped by a thin bed of pumice pellets. The upper foot is a soil zone of humified sand and silt to the present surface. The upper and lower sands with accompanying soils are recognized, but the middle sand is not definitely identified.

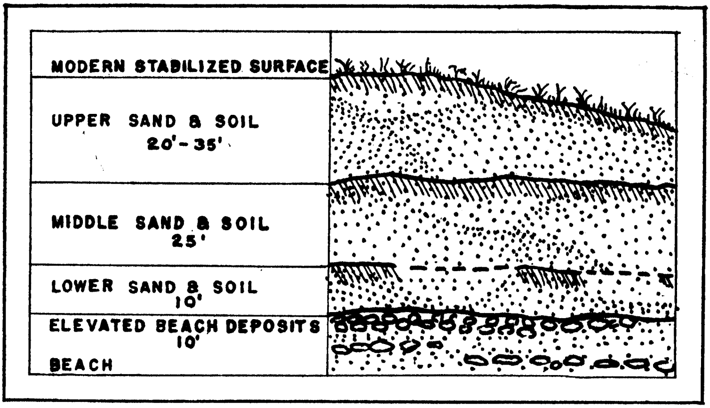

FIG. 3.—Generalized section at Nashville Hill

POLLEN AND DIATOMS OF THE SOILS

Small lenses of peat are present in the soils developed on the three sands. Analyses of the pollen and diatoms contained in random samples of these peats have been made by Arthur S. Knox of the United States Geological Survey. His results are presented in Table 1.

The conclusions from the analyses are limited for several reasons. In the first place, a total of only five samples from the three soils was available for analysis. They may not have been representative of all the Adak peats. Assuming, however, an adequate and representative collection, the use of pollen analysis in the development of a geochronology in the Aleutians is, at present, restricted by other factors. The first of these is that modern vegetation of the area is not well enough known to provide a point of departure in the reconstruction of relative climatic variations of the past. Second, pollen analysis usually relies upon the use of the tree pollen and this will undoubtedly be lacking in most Aleutian peats. Third, no pollen analysis has been previously made in the Aleutians and certainly no general conclusions as to past climates of a large area can be ex-

trapolated from the geographic pin point represented by the present analyses.

In spite of the above restrictions on the use of pollen, it can be pointed out that the absence of tree pollen in the samples indicates that conditions during peat development were no more favorable for tree growth than they are at the present. Knox reports that, although he examined several thousand pollen grains from the samples in addition to those listed in Table 1, the only conifer pollen encountered was a single grain comparable in appearance to *Pinus banksiana*, or scrub pine of the north. This grain was, he writes, "in poor condition and appears to have been transported by wind a considerable distance."

The greatest differences in pollen and diatom content are noted between the topmost soil, on the one hand, and the middle and lowest soils, on the other. Knox refers to peats therein as "fern-sedge peat" and "sphagnum moss peat," respectively. The following conclusions from these differences are quoted from Knox: "The presence of fungi and the lack of sphagnum and diatoms indicate dryer conditions during the development of this layer [peat of topmost soil] than of the others [peats of middle and lowest soils]. The large number and variety of herbaceous plants, as indicated by their pollen, suggest favorable conditions for their growth probably including a

FIG. 4.—Middle sand and soil overlain by upper sand and soil at Nashville Hill.

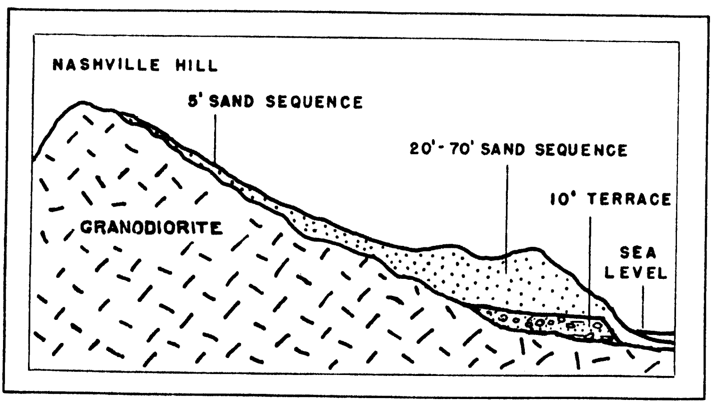

FIG. 5.—Generalized section through Nashville Hill showing relation of the sequence of sand, marine terrace, and bedrock.

warmer climate than during the formation of the other soils."

Knox is unable to state whether the peat of the topmost soil represents a climate warmer than the present. The position of the peat, however, in the horizon of the recent Aleut and close to the modern surface in a soil of accumulation indicates a small time interval between its formation and the present. This would suggest a climate nearly comparable with the present. In turn it might then be said that the two lowest soils were formed under conditions slightly cooler and moister than the present.

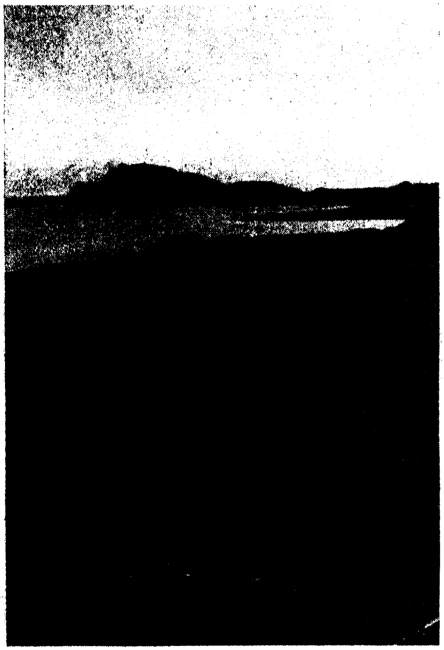

FIG. 6.—Figure-eight pattern resulting from beveling of upper sand and middle sand and soil in Clam Lagoon blowout.

It is unfortunate that there is no information available on the pollen content, if any, of the sands between the soils. The profile is thus interrupted, and we have no indication from this source of the relative nature of the climate intervening between the soils.

ARCHEOLOGY OF THE SANDS

Evidence of human occupation was found in two horizons of the post-till deposits. The soil developed on the latest blown sand carries the artifacts, burials, kitchen middens, and barabaras of the Aleut. Remains are plentiful throughout the sand area and are often found immediately below the soil's yellow, clay-like zone and within a few inches of the modern surface.

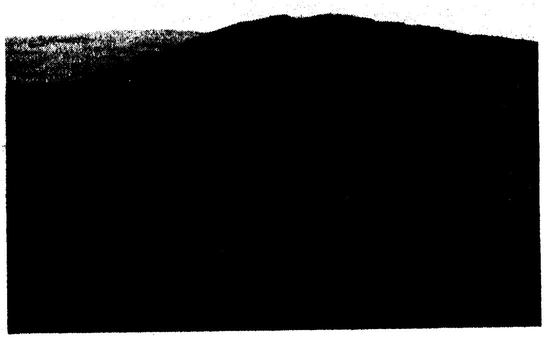

FIG. 7.—Middle sand and soil overlain by upper sand and soil in Clam Lagoon blowout

Evidence of human occupation was also discovered in the next lowest soil, developed on the middle sands. Hearthstones, charcoal, worked flakes, and cores were found in this zone. No diagnostic artifacts could be assigned definitely to the middle soil, although several artifacts, closely associated with it, were found in the Clam Lagoon blowout. As they were not in place, however, they could also have been let down from the youngest soil. One diamond-shaped point, not generally characteristic of the Aleut points, was so found. Similar points have been found from time to time in the Aleutian area, but, like the point in question, their stratigraphic position has not been clearly established.

TABLE 1

DISTRIBUTION OF POLLEN, SPORES, AND DIATOMS IN THE THREE SOILS AS DETERMINED BY ARTHUR S. KNOX

	TOPMOST SOIL*	MIDDLE SOIL†	LOWEST SOIL‡
	Pollen and Spores§		
Fern spores	44.1	1.2	3.0
Sphagnum moss	.6	77.5	66.9
Grass	14.5	10.5	8.1
Sedge	5.5	5.7	10.6
Heath	.3	.3	1.8
Willow	.9	.1	.7
Equisetum	....	2.0	....
Lycopods	....	.4	2.5
Other herbaceous plants	33.2	2.6	8.2
Fungi	Spores and other remains of fungi abundant	....	....
	Diatoms‖		
Pinnularia dactylus	....	frequent	frequent
P. viridis	....	frequent	frequent
P. lata	....	....	common
Navicula semen	....	....	frequent
Diploneis cf. *D. elliptica*	....	....	common

* One sample, 342 spores and pollen counted.
† Two samples, 1,007 spores and pollen counted.
‡ Two samples, 759 spores and pollen counted.
§ Pollen analysis is given in percentage.
‖ Diatoms are listed according to relative frequency.

CHRONOLOGICAL EXTENT OF THE SEQUENCE

The freshness of the till, over which lies the sand-soil sequence, indicates that it is probably Wisconsin, although it is impossible to assign it to a definite stage within the Wisconsin. A certain amount of time, as represented by the weathering of the till, elapsed prior to the deposition of the oldest sand. Whether, however, the sand-soil sequence represents all the

time from the till weathering to the present or whether gaps exist in the sequence is unknown.

ORIGIN OF THE SEQUENCE

Glaciation of Adak and other islands of the Aleutian chain was local in the sense that it was mountain rather than continental glaciation. However, the present mild climate and low altitudes of the island indicate that such glaciation did not exist separately and apart from the major ice advances on the continents. It is felt that the glacial climate represented by the Adak till and the milder postglacial climate represented by till weathering are reflections of, and synchronous with, similar climates obtaining over a large geographic area.

The causes for sand movement and subsequent stabilization following the till weathering are less clear. Formation of sand dunes depends upon the presence of sand, wind capable of moving it, and a place to deposit the sand moved. The stabilization of free sand depends upon the modification or absence of the factors which caused the original sand movement. The presence, modification, and absence of these factors may be either local or of a considerable geographic extent.

Sand supply appears to be the most critical of the three factors involved in this instance of sand-dune formation. Winds are now more than strong enough to move sand and in all probability were equally effective in the past, if not more so. A place to deposit sand has always been available. The supply of sand, however, is limited. It may be increased in two general ways. First, the vegetative cover may be destroyed, thus allowing the winds to remold the already existing dunes. Second, the now narrow beaches, behind which the dunes have collected, may be widened, thereby presenting a greater source area of sand to the transporting winds.

Three local causes may have contributed to the destruction of vegetation and opened old dunes to partial or complete re-working by the wind. They are volcanic activity, fire, and the activity of man and animal. Active volcanoes on Great Sitkin Island to the east and on Kanaga Island to the west may have given off enough ash at various times in the past to destroy the vegetative cover and start sand movement. Ash is found in the lowest soil, and smaller quantities are present in the topmost soil. In neither case, however, has soil development halted with the introduction of ash. These facts, combined with the absence of ash from the middle soil, tend to eliminate volcanic activity as a cause for the initiation of sand movement. No evidence of extensive burned areas was noted within any of the three soil zones. This, too, is discarded as a cause for sand movement. Evidence is lacking to indicate that excessive activity by either man or animal has ever sufficiently destroyed the vegetative cover to permit sand movement. Climatic fluctuation, a nonlocal cause, may be considered as having destroyed the plant mantle to such an extent that sand movement was initiated. Such a climatic shift would of necessity have been extremely violent, and probably only the most rigorous of glacial climates would have driven out all plant life. Moreover, it has already been pointed out that sand has accumulated in spite of the presence of vegetation.

There remains the possibility of widening the beaches to increase the supply of sand. This could be effected by relative movements of land or sea. Such movement could be due either to diastrophism or to eustatic changes in sea-level. The present seismic activity of the area may be offered in favor of land movement. The presence of the 10-foot marine terrace and of elevated beach deposits may also substantiate the theory. However, the complete sand-dune sequence cannot be ascribed to this single terrace; and, furthermore, this terrace may be due to eustatic changes in sea-level rather than to a rise of the land. It is also difficult to accept the theory of the rhythmic rise and fall of land necessary for the alternate exposures and submergences of the beaches demanded by the dune sequence.

Eustatic changes in sea-level to expose and cover the beaches are easier to accept as a premise. It could then be argued that ice accumulations elsewhere drew off enough water to widen the beaches and supply sand for the dunes. Slight ameliorations in climate would raise the water level sufficiently to reduce the sand supply and allow soil development. Although such a mechanism is favored here, the proof is not at hand. Other sand deposits in the North Pacific area must be examined before the contention can be substantiated or rejected.

Despite the belief that climate has played a major and deciding role in the sequence, no attempt has been made to correlate this sequence with known climatic variations of the late-glacial and postglacial in Europe, Asia, and North America. It is felt that the sequence is too isolated geographically to warrant so highly a speculative exercise as such an attempted correlation would demand.

SUMMARY

A late-glacial and postglacial chronology exists on Adak. It is represented by a slightly weathered till, probably Wisconsin, and a marine terrace, followed by three wind-blown sands, each with a developed soil zone. It is suspected that this sequence in its entirety results from climatic fluctuations and is of general distribution throughout a considerable portion of the North Pacific, but lack of ground observations elsewhere in the area precludes a definite statement.

Remains of the recent Aleut are confined to the topmost soil developed on the latest blown sand. Evidence of human occupation in the soil of the second oldest sand presumably indicates either a pre-Aleut people or a somewhat greater antiquity for the Aleut than is usually ascribed to him.

Whether the chronology found on Adak has a wide geographic distribution and, if so, whether cultural remains older than the comparatively recent Aleut are present must be shown by investigations elsewhere in the North Pacific.

Acknowledgments.—The artifacts found on Adak are now in the possession of the Smithsonian Institution and have been examined by Dr. Frank H. H. Roberts, Jr., and Dr. Henry B. Collins, Jr., of that institution. Mr. Arthur S. Knox, of the United States Geological Survey, has most generously provided of his time and knowledge to analyze the peat samples. The brief climatic data have been provided by the United States Army Air Forces. Thanks are extended to Professor Kirk Bryan of Harvard University, and to Mr. Charles E. Stearns, of Tufts College, for critical reading of this paper.

FOSSILIFEROUS PEBBLES IN "PENSAUKEN GRAVEL" AT PRINCETON, NEW JERSEY

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ABSTRACT

Identification of fossils preserved in chert pebbles in the "Pensauken gravel" at Princeton, New Jersey, demonstrates that these pebbles came from Paleozoic rocks of northwestern New Jersey and adjacent parts of New York. They were presumably transported to Princeton by the Delaware River when it flowed, as postulated by Campbell and Bascom, across northwestern New Jersey on its way to Trenton. The fossils do not, however, support Campbell and Bascom's assumption that the Hudson River once joined the Delaware River somewhere in central New Jersey.

There has been much discussion among geologists concerning the origin of the "Pensauken gravel,"[1] which extends in a narrow band across New Jersey from Metuchen to Trenton and thence down the Delaware Valley to Salem and Wilmington. R. D. Salisbury,[2] who studied this gravel 50 years ago, was unable to determine satisfactorily either its origin or the method of its deposition; and it was not until 1933 that Marius R. Campbell and Florence Bascom[3] hit upon an explanation that seemed to fit all the known facts.

Campbell and Bascom explained the peculiar composition and distribution of the "Pensauken" formation by assuming that the Delaware and Hudson rivers had once followed different courses in their lower reaches from those which they now pursue, so that they had joined somewhere between Metuchen and Princeton and had flowed southwestward from their junction to Trenton and thence down the present lower valley of the Delaware River to enter Delaware Bay in the vicinity of Wilmington and Salem, depositing the "Pensauken gravel" in their joint valley from their place of confluence to the sea. These authors presented much evidence in support of this explanation and argued that the combined Hudson and Delaware rivers had occupied this valley for a long time during the Cenozoic era, until deflected into their present youthful lower valleys by Pleistocene ice.

The ancient channel of the Delaware above its junction with the Hudson was

[1] The "Pensauken gravel," as the term has been used by various authors, may include two gravels, one of Tertiary age and one of Pleistocene age. The "Pensauken gravel" which is discussed in the present paper is the one which is distributed from the mouth of the Millstone River southward to the Delaware River and down the Delaware. The gravels found in the valley of the Raritan River, downstream from the mouth of the Millstone River, which have been called "Pensauken," may not have been deposited at the same time as those discussed here.

[2] "Surface Geology: Report of Progress," *Ann. Rept. Geol. Surv. New Jersey for 1893 and 1894*, pp. 33–328 (discussion of Pensauken gravel on pp. 52–60. Also R. D. Salisbury, "The Glacial Geology of New Jersey," *Geol. Surv. New Jersey, Final Rept. State Geologist*, Vol. V (1902) (discussions of "Pensauken gravel" on pp. 190, 541, 715, 722, and 741). R. D. Salisbury and George N. Knapp, "The Quaternary Formations of Southern New Jersey," *Geol. Surv. New Jersey, Final Rept. State Geologist*, Vol. VIII (1917) (discussion of "Pensauken gravel" on pp. 67–159). See also Lester W. Shrock, "A Study of the Pensauken Formation," *Bull. Wagner Free Inst. Sci.*, Vol. IV (1929), pp. 3–10.

[3] "Origin and Structure of the Pensauken Gravel," *Amer. Jour. Sci.*, Vol. XXVI (5th ser., 1933), pp. 300–331.

believed by Campbell and Bascom to have extended in a general southerly direction from Port Jervis, New York, through Culver Gap, New Jersey, past Lake Hopatcong, to a point just west of Bound Brook. They were led to this belief partly because of the existence of large gaps through the mountains at Culver Gap and at the southern end of Lake Hopatcong and partly by the presence in the "Pensauken" of many pebbles of black and dark-blue chert, which had evidently been derived from the Upper Cambrian Kittatinny limestone of Sussex County in northwestern New Jersey.[4]

In assuming that these pebbles of black and dark-blue chert came from the Kittatinny limestone of northwestern New Jersey, Campbell and Bascom were undoubtedly right so far as most of the pebbles were concerned; for, although black chert occurs also in the Devonian Onondaga limestone of the Delaware Water Gap region and areas to the northeast of the Gap that were undoubtedly drained by eastern tributaries of the ancient Delaware, some of the Kittatinny cherts differ from the Onondaga cherts in being oölitic, so that they are easily recognized as having come from the Kittatinny formation. There are, however, many other chert pebbles in the "Pensauken gravel" that are buff in color or partly buff and partly black. None of these pebbles is oölitic; and, although it is probable that most or all of them were originally black and have become buff because of very long exposure to the agents of weathering, they look as though they had come from some other formation than the Kittatinny limestone.

No one appears to have undertaken to determine the origin of these buff pebbles, earlier students of the "Pensauken" having apparently assumed that there was no means by which it could be done

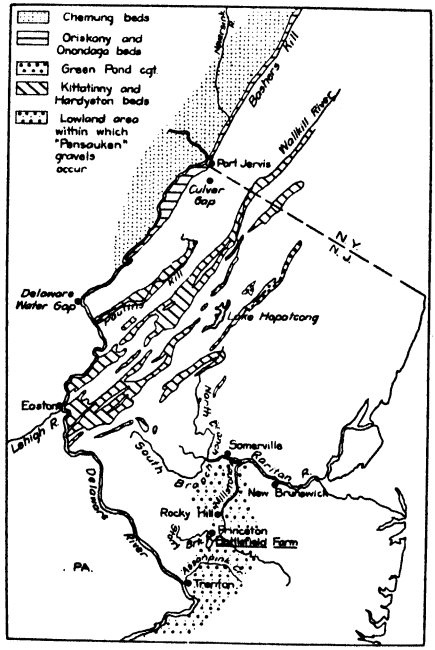

FIG. 1—Map of northern New Jersey and adjacent portion of Pennsylvania, to show distribution of "Pensauken gravel" and of Paleozoic formations, from which fossiliferous pebbles found at Princeton were derived.

satisfactorily. Therefore, the recent discovery by the writers that in at least one locality in Princeton Township, Mercer County, many of them contain Onondaga fossils, which indicate that they were derived from the Onondaga limestone of Sussex County, New Jersey, or from adjacent parts of New York, is believed to be worthy of record.

These fossiliferous pebbles were found on Battlefield Farm, a part of the site of

[4] Campbell and Bascom appear to have written "Essex County" where they intended to write "Sussex County" in l. 32 of p. 310 of their paper, for there is no Kittatinny limestone in Essex County from which the black and dark-blue chert pebbles to which they there refer could have been derived.

the Revolutionary battle of Princeton. This farm, which was for many years owned by members of Dr. Hale's family, lies on the eastern side of Stony Brook, just southwest of the town of Princeton. The highest land on the farm (where the house is situated) is some 120 feet above sea-level and is composed of "Pensauken gravel." It was from the surface in the vicinity of the house that the fossiliferous pebbles were collected by Dr. Hale. The pebbles are Nos. 57881–57888 and 58192–58300 in the stratigraphic collection of Princeton University.

Associated with the buff-colored chert pebbles containing the Onondaga fossils, Dr. Hale found black chert pebbles (some of them oölitic, but none of them fossiliferous) from the Kittatinny limestone; a few pebbles of other kinds of rocks, whose fossil content or lithologic character indicate that they came from other Paleozoic formations; some pebbles that must have come from the pre-Cambrian rocks of northwestern New Jersey; and a small number of limonitic pebbles that were probably derived from the unconsolidated Cretaceous deposits which are believed to have formed the southeastern (left) flank of the valley through which the combined Hudson and Delaware rivers are thought to have flowed between their point of junction and Trenton.

A careful study of some two hundred pebbles collected from Battlefield Farm enables us to state that, on the evidence of their fossils or of easily recognizable peculiarities of lithology, they had the following origins:

pre-Cambrian (formation undetermined, one pebble contains graphite)
Hardyston sandstone, Lower Cambrian
Kittatinny limestone, Upper Cambrian
Green Pond conglomerate, Silurian
Middle Silurian (formation undetermined)
Oriskany formation, Lower Devonian
Onondaga limestone, Middle Devonian
Chemung formation, Upper Devonian

The identification of the pre-Cambrian, the Hardyston, the Kittatinny, and the Green Pond pebbles is based solely on lithology. All the other identifications are based on fossil evidence. The following fossils were found:

MIDDLE SILURIAN (FORMATION UNDETERMINED)

Howellella crispa (Hisinger)

ORISKANY FORMATION, LOWER DEVONIAN

Acrospirifer murchisoni (Castelnau)

ONONDAGA FORMATION, MIDDLE SILURIAN

Favosites turbinatus Billings
F. goldfussi d'Orbigny
Heterophrentis nitida (Hall)
Polypora celsipora (Hall)
Chonetes mucronatus (Hall)
Atrypa reticularis (Linne)
Acrospirifer duodenarius (Hall)
Brevispirifer gregarius (Hall)
Microspirifer macrus (Hall)
Delthyris raricosta Conrad
Cyrtina hamiltonensis (Hall)

CHEMUNG FORMATION, UPPER DEVONIAN

Leiorhynchus mesacostalis (Hall)

A single small slab of limestone that almost certainly came from an outcrop of the Kittatinny formation is of special interest because it is so easily soluble and abraded that it can hardly have been carried for any great distance by a stream and must have come from one of the bodies of Kittatinny limestone in Hunterdon, Warren, or Morris counties, New Jersey.

The pre-Cambrian, the Hardyston, and the black chert (including the oölitic black chert) pebbles probably also came from Hunterdon, Warren, Morris, or Sussex counties; and the Green Pond pebbles probably originated in Morris County. The Middle Silurian, the Onondagan, and the Chemung pebbles prob-

ably came from somewhere in New York, as beds of these formations are either lacking in New Jersey or are found only along the New Jersey–New York state boundary. The black Kittatinny limestone chert pebbles are not so well rounded as the buff chert pebbles from the Onondaga limestone, for the Kittatinny pebbles did not travel so far as the Onondaga ones. The present buff color of the presumably once black Onondaga chert pebbles indicates that they were on the road for a much longer time than the Kittatinny chert pebbles, which are always black or bluish-black in color. The Onondaga pebbles, at least, may well have started on their way in Tertiary times.

The land surface from which these pebbles were collected is now some 60 feet above the bed of Stony Brook, which flows near by. As noted above, some of the pebbles on this surface came from northwestern New Jersey and adjacent parts of New York, and those which appear to have come from such New York formations as the Onondaga limestone look as though they had been in transit at least since Pliocene times. As no marine fossils have been found in the matrix of the "Pensauken gravel," it was probably transported entirely by fresh waters. The pebbles on Battlefield Farm could hardly have been brought there by the present Delaware River, whose bed is at sea-level at Trenton. They could not have been brought there by Stony Brook, whose headwaters do not extend far enough northward to have gathered them from their parent-ledges. They show no evidence of having been picked up by a glacier and either transported by it to Battlefield Farm or delivered by it to an ancestor of Stony Brook, which, then flowing at a higher level, might have deposited them in their present resting place. It seems almost certain that they, like the rest of the pebbles of the "Pensauken gravel," must have been rolled along in the bed of a large river of Tertiary or very early Pleistocene age[5] whose headwaters were in New York and which was later deflected from its ancient channel in New Jersey by Pleistocene ice (and possibly also by crustal warping), so that only its gravels remain to mark its course across central New Jersey.

In other words, the evidence of our Battlefield Farm pebbles supports Campbell and Bascom's theory that the ancient Delaware flowed southward from Port Jervis across northwestern and central New Jersey to the vicinity of Trenton. No other theory affords a satisfactory explanation of the presence of these pebbles at Battlefield Farm. Indeed, the proof afforded by their fossils of the sources of many of the pebbles greatly increases the probability that the Delaware once followed such a course.

Our pebbles do not, as far as we have been able to observe, present any clear evidence that the waters of the Hudson River also flowed over Battlefield Farm, as Campbell and Bascom postulated. Some of our pebbles may have been delivered to the Hudson by western tributaries and then transported to Princeton via an old channel of that river, such as was postulated by these authors; but, since the pebbles may have been carried from their parent-outcrops more easily

[5] P. MacClintock and H. G. Richards ("Correlation of the Late Pleistocene Marine and Glacial Deposits of New Jersey and New York," *Bull. Geol. Soc. Amer.*, Vol. XLVII [1936], p. 335) consider the "Pensauken gravel" to be of early Pleistocene age. Richards ("Correlation of Atlantic Coastal Plain Cenozoic Formations: A Discussion," *Bull. Geol. Soc. Amer.*, Vol. LVI [1945], p. 402) states more specifically that it is probably "Nebraskan to Yarmouth" in age, "thus representing both glacial and interglacial stages."

by the waters of the ancient Delaware, we have no reason to assume that they were brought to Princeton from the Hudson watershed. A single piece of serpentine, found by Dr. Hale, looked as though it might have come from the body of serpentine near Boonton, New Jersey, whence it might have been transported to Princeton via the lower valley of the ancient Hudson; but this piece was not a rounded, water-worn pebble, and it may have been carried to Battlefield Farm by man.

It is very desirable that additional collections of pebbles—especially of fossiliferous pebbles—be made from the "Pensauken gravel" at other localities; for such collections, when their fossils have been identified, may afford definite evidence concerning the late Tertiary and early Pleistocene history of central and northern New Jersey. When more such collections have been secured and studied, we shall probably be able to complete the proof of the existence of an ancient Delaware River that flowed well east of the present Delaware between Port Jervis and the vicinity of New Brunswick; and we may be able to determine with certainty whether the ancient Hudson, too, flowed westward to join the Delaware near New Brunswick and go with it past Princeton to the present Delaware Valley near Trenton and so, via Delaware Bay, to the sea.

J. B. Lucke[6] has presented evidence of the existence of a pre-"Pensauken" river that flowed from the northwest across New Jersey and into Raritan Bay. The river which deposited the "Pensauken gravels" may well have followed originally the course of this older stream almost, or quite, to its mouth and may later have been deflected westward by the early Pleistocene Jerseyan glacier and by coastal warping, so that it flowed past Princeton to the lower Delaware Valley from Jerseyan times until the date when the Delaware River began to follow its present course from Port Jervis to Trenton. MacClintock and Richards[7] have called attention to the presence, beneath Jerseyan till in some localities in central New Jersey, of gravels and sands that may have been deposited in the valley of such a pre-"Pensauken" river as Lucke has postulated.

If future discoveries indicate that the ancient Delaware flowed across central New Jersey and down the lower valley of the present Delaware River to the ocean, it will be necessary to give that river a name. As the name "Pensauken" is not available, there being already a Pensauken Creek in New Jersey, and as "Princeton" would be a logical and appropriate name for such a stream, we propose that it be called the "Princeton River."

It is very desirable that a geophysical survey be made to determine the course and depth of the valley of the stream that once flowed through Culver Gap and probably ran past Lake Hopatcong. If the location and the elevation at a number of points of the rock floor of this old valley can be determined by geophysical soundings (as they probably can be), the final evidence of the course, and much information about the age and size, of the river will be secured. It is hoped that such a survey will be made in the near future.

[6] "Gravel Indications of New Jersey Drainage Changes," *Jour. Geomorph.*, Vol. IV (1941), pp. 265–84.

[7] Pp. 229–300, Pl. I, Fig. 2, of ftn. 5.

GLACIAL BASTIONS IN NORTHERN COLORADO

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ABSTRACT

Three well-developed glacial bastions in northern Colorado are described, their age and mode of origin indicated, and their similarity to glacial bastions elsewhere stated. Bastions in other areas in North America are mentioned.

INTRODUCTION

Although glacial bastions are by no means rare features of European glacial landscape, many standard texts make no mention of them.[1] Because of this omission, many students, and not a few professional geologists, are quite unacquainted with these features in the continental United States.

During field work in the mountainous portion of northern Colorado[2] a number of bastions and a larger number of bastion-like features were found. Three of these, which were investigated in some detail, will be described. Locations are shown in Figure 1.

MONITOR ROCK

Monitor Rock, located at the junction of Monitor Gulch with Lake Creek, about 2½ miles WSW of the Twin Lakes post office, in Lake County, Colorado, was accurately described, although not designated as a bastion, by S. R. Capps in 1909.[3] This area is somewhat sketchily shown on the United States Geological Survey Leadville Quadrangle sheet (1/125,000 [1891]). An excellent photograph of Monitor Rock by Westgate, which was used in Capps's report, is reproduced as Figure 2.

Monitor Rock is composed of hard, fine-grained, light-colored granite (field classification), remarkably free from joints. Its height is approximately 350 feet; and at the top the structure projects about 150 feet into the valley of Lake Creek. The upper surface is grooved and striated parallel to the axis of Monitor Gulch; the face, although polished, is not grooved or striated. Well-developed glacial grooves, parallel to the axis of Lake Creek Valley, are present in many places between Twin Lakes and Independence Pass. Local topographic relations are sketched in Figure 3.

Field studies indicate that the grooving and striations on Monitor Rock date from one or more of several mid-Wisconsin glaciations, roughly homologous with W. D. Jones and L. O. Quam's Park Border Moraines[4] or with R. L. Ives's River-Arapaho sequence.[5] The upper

[1] A notable exception is O. D. von Engeln's *Geomorphology* (New York, 1942), which includes a brief clear description (pp. 459–61) and an excellent illustration (Fig. 268).

[2] Field work in part assisted by grants from the Penrose Fund of the American Philosophical Society.

[3] "Pleistocene Geology of the Leadville Quadrangle, Colorado," *U.S. Geol. Surv. Bull. 386* (1909), p. 57.

[4] "Glacial Land Forms in Rocky Mountain National Park, Colorado," *Jour. Geol.*, Vol. LII (1944), pp. 217–34.

[5] "Glacial Geology of the Monarch Valley, Grand County, Colorado," *Bull. Geol. Soc. Amer.*, Vol. XLIX (1938), pp. 1045–66; and "Glacial Geology of the Colorado Headwaters Area, Colorado" (in preparation). Field checking in the Colorado headwaters area by Quam and in the Estes Park area by

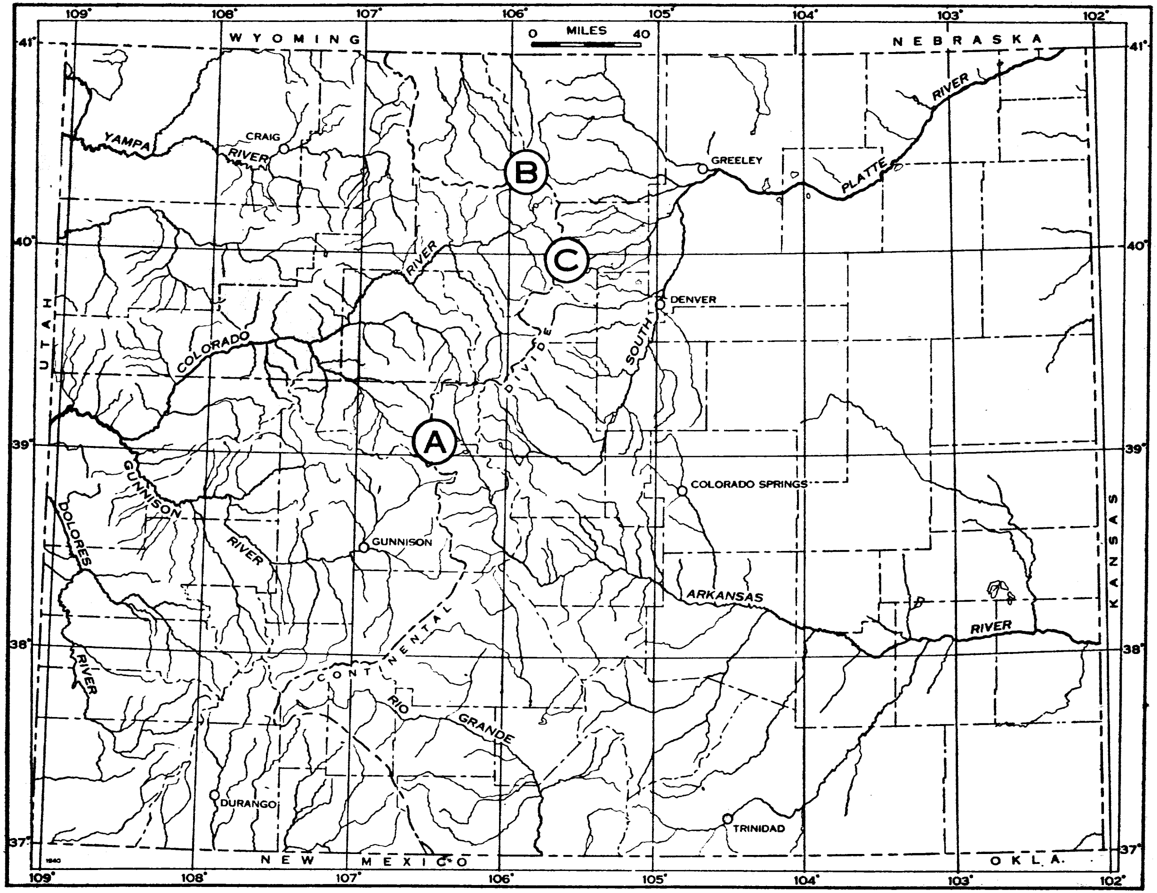

FIG. 1.—Outline map of Colorado, showing locations of bastions studied. *A*, Monitor Rock; *B*, the Hitchens Gulch bastion; *C*, the Silver Lake bastion.

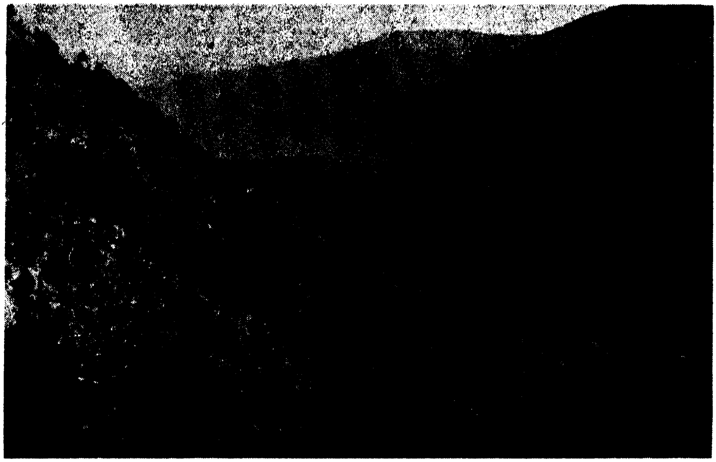

FIG. 2.—Monitor Rock, in Lake Creek Valley, Colorado, seen from the west. This excellently developed bastion is plainly visible from the Twin Lakes–Independence Pass road and is one of the very few easily accessible bastions in Colorado. (After Westgate.)

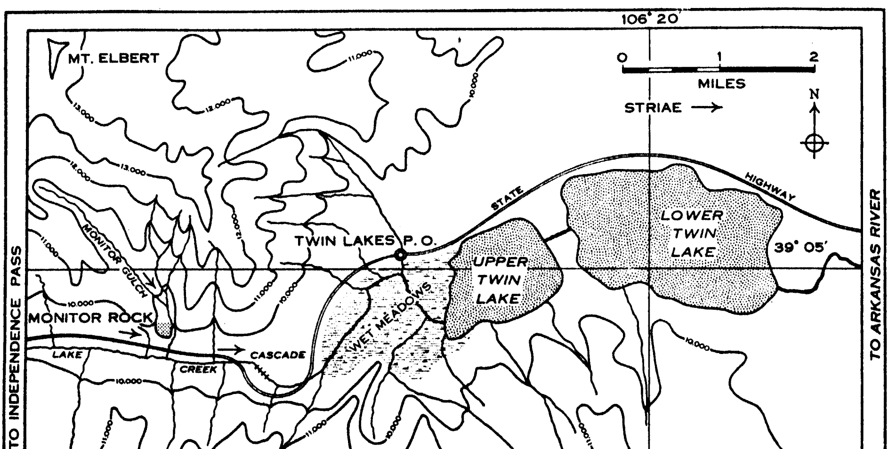

FIG. 3.—Sketch map of Monitor Rock and vicinity, showing drainage, directions of striae, and principal local features.

border of the ice in Lake Creek Valley at that time was approximately 100 feet above the top of Monitor Rock; and the ice in Monitor Gulch, a few hundred feet upstream from the junction, was about 200 feet thick.

Although there is no good reason to believe that the ice in both valleys did not attain maximum thickness at the same time, all that is shown by field evidence is approximate simultaneity.

THE HITCHENS GULCH BASTION

The Hitchens Gulch bastion is located on the north side of the gulch, which is near the head of the Colorado River, in the Never-Summer Range, Grand County, Colorado. This area is shown on the United States Geological Survey, *Rocky Mountain National Park*, quadrangle map (1/125,000 [1909]; specific location SW. ¼, Sec. 35, T. 6 N., R. 76 W.), which is not very accurate at this particular place. One view of the form comprises Figure 4.

This bastion, composed of hard volcanic breccia, is about the same size as the Lake Creek bastion, exact measurement being difficult, as the base is concealed by talus, moraines, and rock-glacier materials.[6] No glacial striae were found on the upper surface or on the face of this bastion. Because the rock weathers rapidly, such surface features are not likely to be preserved.

In the absence of better evidence, this rock boss was assumed to date from the last glaciation which had an upper ice surface above the top of the bastion. Reconstruction of ice profiles in the area indicates that this was not later than the River glacial stage, first of three mid-Wisconsin advances. So old is this boss that the cirque in the tributary valley above it has been largely removed by erosion and landslips.

Field evidence suggests that an ice cascade, of short duration, passed over the east (right, Fig. 4) side of this bastion after the main profile was completed. Because of the nature of the rock at this site and the relatively long time since any ice passed over the bastion it cannot be stated whether the time interval between the formation of the main bastion and the existence of the ice cascade was a few dozen or a few thousand years.

Several other bastions, poorly preserved, and perhaps not very well developed originally, are present in this and adjacent valleys. All, so far as can be determined from the evidence now available, are about the same age.

THE SILVER LAKE BASTION

The Silver Lake bastion is located on the south wall of the Silver Lake Valley, about 2½ miles down-valley (east) from the Arapaho Glacier. This area is shown (quite accurately) on the *Rocky Mountain National Park* topographic sheet (specific location NW.¼, Sec. 30, T. 1 N., R. 73 W.). This valley has been studied in considerable detail by a number of workers during the last four decades. A summary report on the area is in preparation.[7] Figure 5 shows the Silver Lake bastion and its surroundings.

The Silver Lake bastion is composed entirely of Boulder Creek granite, which is very resistant to all forms of erosion, but which has a well-developed set of joints, which here strike S. 70° E. and

Ives indicates that the Park Border moraine sequence of Estes Park is homologous with the River-Arapaho moraine sequence of the Colorado headwaters area.

[6] R. L. Ives, "Rock Glaciers in the Colorado Front Range," *Bull. Geol. Soc. Amer.*, Vol. LI (1940), pp. 1271–94.

[7] R. L. Ives, "Glaciation in the Silver Lake Valley, Colorado" (in preparation).

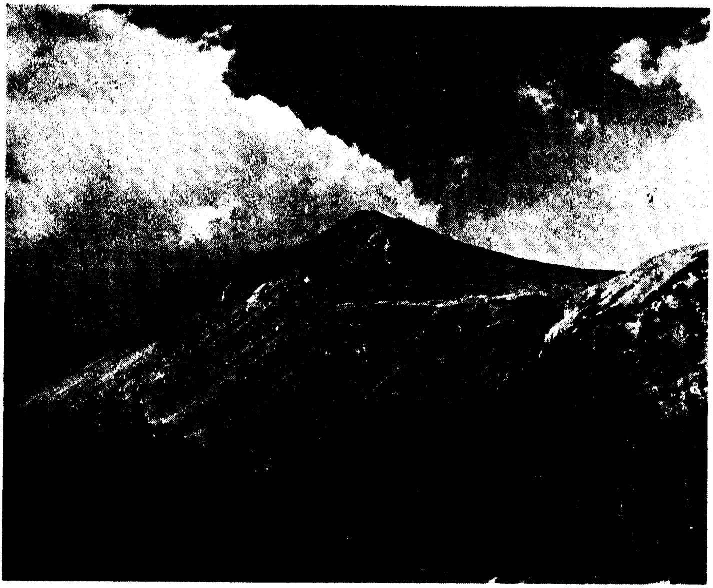

FIG. 4.—The Hitchens Gulch bastion, seen from the southeast

FIG. 5.—Infrared photograph of the Silver Lake Valley from North Arapaho Peak (13,506 feet), showing major features of a complicated, multiply glaciated valley. The bastion is visible in the center of this view, to right of lakes. Note glaciated bench on left side of valley. Moraine of Arapaho Glacier is visible in lower-left foreground.

dip approximately 45° (see Fig. 5). Along these joints, blocks of granite break away rather easily, so that glacial erosion of the south wall of the valley was largely by quarrying rather than by abrasion.

The upper surface of this bastion is covered with a thin layer of alpine soil, which supports a lush growth of grass. Exposed rock is beautifully polished, but not striated or grooved. A few small potholes are present in this area and are attributed to weathering rather than to stream-of-glacier erosion. Rock beneath the soil, as exposed in several excavations, is smoothly polished, but also neither striated nor grooved.

The face of the bastion is neither glacially polished nor striated, in most places, but consists of smooth planes produced by parting along the steeply dipping joints (locally called "stratification").

The tributary glacier which once flowed over this bastion had its source in a small valley near the summit of Bald Mountain (12,753 feet MSL, SE.$\frac{1}{4}$, Sec. 25, R. 1 N., R. 74 W.). Reconstruction of glacial profiles indicates that the bastion was formed during a stage when the valley floor was about 250 feet above its present level. This condition could not have prevailed later than the building of the Albion moraine, oldest and largest of the three attributed to mid-Wisconsin glacial advances (beyond lakes, Fig. 5). It is quite probable, although not rigorously shown by field evidence, that ice cascaded over this structure from the relatively small and feeble Bald Mountain Glacier during one or more later glacial advances, producing a typical ice cascade.[8] During the latest group of Wisconsin glaciations, which built the moraines about and between the lakes in Figure 5, this tributary valley was not glaciated.

[8] Fig. 268 of ftn. 1.

BASTIONS IN OTHER AREAS

Numerous reconnaissances have disclosed that there are other glacial bastions in Colorado, such as the group near the headwaters of Middle Boulder Creek,[9] and that many can be found in the Uinta, Wasatch, and Sierra Nevada ranges. Unfortunately, most of these structures are in extremely inaccessible locations, and a few are in valleys not even shown on the inadequate maps available today.

Study of a large number of aerial photographs from the western United States, Alaska, South America, and the Himalayan regions suggests that, although no large glaciated mountain region is without bastions, they are not present in all valleys and that, in intensely glaciated regions, one bastion may be present for each four major glacier systems.

FORMATION OF BASTIONS

Bastion formation cannot be observed directly, for it occurs under a relatively thick cover of ice. While it may be possible, by geophysical methods, to locate a bastion beneath a present glacier and to study the changes in its configuration by remapping every generation or so, this has not been done to date nor, so far as known, has it been attempted.

Inference from physical theory indicates that a bastion may form wherever a tributary joins a trunk glacier if: (*a*) a discordance of levels exists or is produced and (*b*) the lateral thrust of the tributary inhibits lateral erosion by the trunk glacier beneath the junction.

[9] A thorough study of this area, by Dr. P. G. Worcester of the University of Colorado, is now in progress.

Because bastions are not always formed when these conditions would seem to have been met, a number of experiments, in which the bedrock was simulated by wet casting sand, and the ice by a cohesive mixture of Jello and corn syrup,[10] were undertaken. These indicate that bastion-like shapes are usually produced in the sand by simulated ice motion when the angle included between the upstream portions of the two "glaciers" exceeds 40° and when the base of the tributary is above the center of the simulated trunk "glacier." However, because of the difference in properties and in scale between the experimental materials and those in nature, this limiting angle, although seemingly within reason, may have little geologic significance.

Although deepening of the main valley where constricted by a bastion is called for by the "law of adjusted cross sections," and has taken place in many field cases, it was not produced by these experiments.

[10] Although this mixture has many of the properties of ice, including regelation, its use is extremely messy, as the compound ferments, acquires a nauseating odor, and attracts insects. Addition of one-fourth of 1 per cent arsenious acid to the mixture reduced these difficulties considerably. A mixture of neoprene "latex" (costly) and machine oil was also tried with some success.

CONCLUSIONS

Glacial bastions occur in the United States as well as in Europe and Alaska, and it is probable that some bastions are present in all large glaciated mountain areas as normal landscape features.

Field evidence and experiments indicate that bastions are formed when a tributary glacier at a relatively high level inhibits by its thrust the lateral erosion by the main glacier at the point of junction.

It is the opinion of this writer that the apparent rarity of glacial bastions is due more to lack of recognition than to nonoccurrence and that, when more thorough studies are made of the higher and less accessible portions of glaciated mountain ranges, this apparent rarity will disappear. Much information on this subject could be secured by a thorough study of the aerial photographs now in the files of the War and Navy departments.

Acknowledgments.—The writer is indebted to Dr. François E. Matthes, of the United States Geological Survey, for many helpful and informative discussions of glacier mechanics; to the late Captain George Langham, A.C., for a reconnaissance flight over the Uinta Mountains; and to M/Sgt. Israel M. Weinberg, Q.M.C., for the procurement, preparation, and disposal of five hundred pounds of simulated ice used in experimental work.

DISCUSSION: THE ORIGIN OF NEPHELINE ROCKS IN ONTARIO

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Students of the feldspatshoidal rock have reason to welcome the recent activity of the aluminum and ceramic industries in the Bancroft and Methuen districts of Ontario. This activity has not only stimulated the geological mapping of the country and yielded valuable three-dimensional evidence from boreholes, but it has revived a healthy controversy about the genesis of the nepheline-bearing rocks.[1]

A geological map of the Bancroft area on the scale of 1,800 feet to 1 inch was made by F. Chayes and published in 1942. A new map of the same area has since been made by W. K. Gummer and S. V. Burr for the Aluminum Company of Canada and the American Nepheline Corporation; this was published on a scale nearly three times that of Chayes' map, and it is correspondingly richer in detail. Chayes has acknowledged that "the Gummer-Burr map is characterized by considerably less extrapolation than mine; and its location of specific outcrops or quarries is in general to be preferred." It is natural to inquire whether the new study of the area has led to a fuller understanding of the genetic problem.

In the matter of petrography, Gummer and Burr have found little to add to the accurate descriptions given by Chayes and by the great pioneers, Adams and Barlow. There are some changes of nomenclature which tend to obscure a fundamental agreement, as explained below.

The "paragneiss and schist" of Gummer and Burr is the same rock formation as the "syenite and shonkinite" of Chayes. These names were used by Chayes in a purely mineralogical sense to cover a complex of intrusive and hybrid rocks which could not be separated in mapping. Chayes wrote that "the hybrids are streaky heterogeneous gneisses of shonkinitic composition."

The "nepheline paragneiss" of Gummer and Burr comprises those younger or second-degree hybrids to which Chayes gave the mineralogical names "foyaite," "ijolite," and "jacupirangite." Chayes wrote that these rocks "seem to have been formed by the injection of urtite magma into previously solid amphibolite and syenite."

There is little doubt that most of the rocks in question were formed from original sediments and are therefore paragneiss, but some of them may be orthogneiss, either contaminated granite or amphibolized gabbro, as Adams and Barlow suggested and as Chayes too indicates. For this reason it seems undesirable to insist on the prefix "para" when referring to the series as a whole. What is needed is a very wide blanket name such as "Bancroft migmatite series," with recognition that the series is made up of paragneiss, orthogneiss, and migmatite of many kinds. Only a small part of this series is nepheline-bearing.

The matter which specially interests us is the genesis of nepheline in these

[1] See especially W. K. Gummer and S. V. Burr, "Nephelinized Paragneisses in the Bancroft Area, Ontario," *Jour. Geol.*, Vol. LIV (1946), p. 137, and other references therein.

gneissic rocks. There are two main kinds of nepheline-bearing rocks in the Bancroft area: the pegmatites, which have a very simple composition (if we disregard trace elements), and the schistose foyaite or nepheline gneiss, which has a wide range of chemical and mineralogical composition. Chayes claimed that the schistose foyaite was formed by the injection of an urtitic liquid (that is, a liquid having nearly the composition of nepheline) into syenite and amphibolite. A similar opinion regarding the nepheline gneiss at Egan Chute was expressed by F. F. Osborne in 1930. Chayes was able to show that the nepheline-bearing gneiss in the Bancroft district passes by simple decrease in the frequency of the urtitic folia into syenitic gneiss containing only occasional "eyes" or lenticles of urtite and then into nepheline-free gneiss. In Chayes' words, these observations "afford the most convincing evidence of the permeation of syenite by an urtitic liquid."

Chayes argued that this urtitic liquid "was in some fashion derived from the parent liquid of the granites and pegmatites" and further that "the mineralogy of the Haliburton-Bancroft field favors the limestone-syntexis hypothesis" of R. A. Daly. But Keith, Gummer, and Burr maintain, in opposition to Chayes, that the granite is younger than the nepheline rocks and intrusive into them; they hold that this refutes or puts difficulties in the way of limestone syntexis. All that the evidence entitles them to say, however, is that *some* of the granite is younger than the nepheline rocks. Chayes observed that these rocks are in some instances cut by granite-pegmatite, but he recognized that this dates the *end* of the period of granitic intrusion, not its beginning. The limestone-desilication hypothesis does not require that the whole of the reacting magma be desilicated; indeed it has been shown repeatedly that the proportion of feldspathoidal rock formed in any complex is only an inconsiderable fraction of the magma involved. Chayes computed that the whole amount of saturated and undersaturated rock in the Bancroft area constitutes no more than 1 per cent of all the eruptive rock present. Is it difficult to believe that an early intrusion of granitic magma reacted locally with limestone and that later injections of the same magma sometimes intersected the earlier rocks?

Try as he may to avoid limestone-syntexis and desilication of granitic magma, every petrologist who has studied the Bancroft area has been compelled to recognize this reaction sooner or later. Gummer and Burr claim that "there is no field evidence . . . . of the production of nepheline-syenite magma through reaction between solid limestone and granite magma"; but two pages further on they confess that "it is impossible to escape the conclusion that calcite has played some prominent role in the formation of the nepheline rocks." In another place they say that "the nepheline rocks were formed *in situ* by some process of replacement" and add that "the introduced materials contained soda and alumina and apparently not much silica." They favor the idea that the soda and alumina were derived from a granitic or syenitic source, but they do not try to explain how a granitic differentiate can be so poor in silica as to generate nepheline instead of albite in the rocks which it invades.

It is to be regretted that Gummer and Burr are so reluctant to admit the direction toward which they are driven by their own observations. They say "if the nephelinizing solutions were actually albitizing solutions which underwent de-

silication through reaction with $CaCO_3$ . . . . then the reaction was outwardly similar to Daly's postulate." Outwardly similar? The reaction that they describe in the foregoing sentence is Daly's reaction and nothing less!

The nepheline-forming solution pictured by Gummer and Burr seems to be little if at all different from Chayes' urtitic magma. The latter should not be thought of as molten nepheline but as a hot aqueous solution of soda, alumina, and silica in the proportions of 1:1:2 or more (but less than 6). In the field the writer formed the impression that the solutions which generated nepheline in the gneissic rocks were the same solutions which generated the nepheline pegmatites. Indeed the little eyes and lenses of urtite in the gneisses are just small bodies of nepheline pegmatite. Chayes too concluded that "the pegmatites were the source of the nepheline now found in the gneisses"; and so did Osborne at Egan Chute. But because nepheline pegmatite sometimes cuts the nepheline gneiss, Gummer and Burr think that a different origin is indicated. They suggested in 1943 that "many of the nepheline pegmatites appear to be the result of the regeneration of the nepheline of the paragneisses." This idea is put forward again in the later report, but only as a speculation. It appears to the writer, as it did to Chayes, to be unjustified. Nepheline is so easily hydrolyzed that its regeneration "in the presence of introduced materials" (which can mean only water) is highly unlikely.

We must now give some attention to the view of Louis Moyd.[2] Moyd says first that "most of the nepheline-bearing rocks are migmatites, formed from pre-existing rocks of the Grenville series." In this he is in accord with all recent students of the subject. He next pictures the intrusion of granitic magma into the Grenville and says, "some of the magma would react with the dolomitic marbles, releasing emanations [which would] lose much of their silica, forming granitic and syenitic migmatites, and finally, impoverished in silica, would form more unusual migmatites." Since any further reduction of silica, beyond the syenitic stage, must lead to the generation of nepheline, this is just Daly's hypothesis all over again; but now a curious twist is introduced. Moyd says that "these mineralizer-rich emanations could convert the high-lime feldspars of the dark gneisses to alkali-feldspars, releasing alumina to form nepheline or corundum." Since the emanations have already been desilicated far enough to yield potential nepheline, one wonders why it should be thought necessary to bring lime-rich feldspar into the matter and indeed what authority there is for assuming the presence of this kind of feldspar in the Grenville rocks. If Moyd were describing a replacement which he had observed under the microscope, then his statement might be accepted without question—we shall see that this very replacement has been observed elsewhere—but the printed abstract suggests that Moyd is offering us a speculation, not an observation. The one essential factor in Moyd's discussion is just Daly's reaction.

The term "nephelinization" has been used by recent writers to describe the generation of nepheline in the Bancroft gneisses. According to Gummer and Burr the new term is used "to specify the end-result, and does not imply that nepheline was, or was not, added as such." (Nepheline could not be added "as such,"

[2] "Petrology of the Nepheline and Corundum Bearing Rocks of S.E. Ontario," abstract in *Bull. Geol. Soc. Amer.*, Vol. LVI (1945), p. 1183.

because the name is only applicable to the crystalline solid, not to a solution.) Although the term "nephelinization" is new, the idea that a solid rock may be impregnated with nepheline by solutions derived from a later intrusive is not new. As long ago as 1891, J. H. Sears described the essexite of Salem Neck, Massachusetts, and noted the presence of "numerous patches of elaeolite and perhaps sodalite" within the large plagioclase crystals. The observation was confirmed by Rosenbusch (1907); but C. H. Clapp described the mineral as microperthite.[3] The writer has treated thin sections of the Salem essexite with phosphoric acid and methylene blue and finds that the foreign substance in the plagioclase is gelatinized and stained with the same ease as nepheline. Since analcime and sodalite are excluded by the refractive index, the substance can be only nepheline.

These observations seem to fall into line with Moyd's speculation. But Rosenbusch observed, and the writer confirms the observation, that the rocks which show these intergrowths of plagioclase and nepheline are cut by dikes of foyaite which clearly furnished the necessary sodic solutions. Whether the intergrowths were formed by ionic substitution of Na_2 for Ca or by simple deposition of nepheline in cracks in the plagioclase crystals has not been clearly established. But since the foyaitic source rock itself contains nepheline, it cannot be maintained that reaction with plagioclase is a necessary step in the generation of nepheline. Nothing resembling these plagioclase-nepheline intergrowths has been observed in the Bancroft migmatites.

The Bancroft area has now been mapped and studied perhaps more closely than any other area of nepheline-bearing rocks in the world, and at least nine geologists (all those who have placed their conclusions on record) have failed to find any substitute for Daly's hypothesis of the genesis of the nepheline rocks in this area.

[3] *U.S. Geol. Surv., Bull. 704* (1921), p. 124, and Pl. XVIII.

REVIEWS

NEW SCIENTIFIC DATA FROM FINLAND

With the restoration of mail service, the Finnish workers in earth science have sent abroad many brochures and monographs, in number and quality truly astonishing when one reflects on the grievous conditions of scientific research for seven years. These publications have been issued in journals and other series which are not readily accessible to many geologists and geophysicists in North America. Even a brief and incomplete notice of leading results from some of the investigations may therefore be useful to readers of the *Journal of Geology*.

The first work to be here listed is V. Tanner's 907-page, large-octavo book entitled *Outline of the Geography, Life and Customs of Newfoundland-Labrador*, Volume VIII of *Acta Geographica* (Helsinki, 1944), illustrated with 342 maps, diagrams, and photographs. The book, in excellent English, is a remarkably thorough summary of what is known about the physiography, geology, coastal waters, meteorology, botany, zoölogy, anthropology, and human conditions of Labrador, particularly of the 285,000 square kilometers included in that part of the peninsula now under Newfoundland authority—about one-sixth of the peninsula as a whole. The resulting compilation, based on study of more than eleven hundred books and papers named in the Bibliography, has been done with skill and discrimination.

The new field observations recorded were made during explorations in the summers of 1937 and 1939. Their principal object was to work out the "epeirogenic spectrum" of Labrador and to compare it with that of Fennoscandia, which had been described by Tanner in *Bulletin 88 of the Commission Géologique de Finlande* (1930). It was hoped that "the isochronous beach-surfaces and their deposits will be automatically and definitely identified on both sides of the North Atlantic" so as to "enable us to reconstruct the late- and post-Glacial isochronous paleogeographic development in respect of topography, climate, biology, and archaeology for the two northern continents" (p. 234). For reasons patent to anyone familiar with the raised beaches of Labrador, the development of the epeirogenic spectrum was bound to be a much more difficult feat than in Fennoscandia. Such relevant field observations as could be made in the two short seasons still, in 1944, needed further correlation; for this reason only a few notes on the spectrum problem appear in the book. Tanner intends to issue a full report on this subject later.

It is to be hoped that the promised report will contain maps showing localities where heights of the raised beaches are stated. A second clarification is needed in connection with the problem of the marine limit for the emerged belt along the northeast coast. In his exploration in 1900 the present writer found that at any shoreward profile examined the limit is somewhat higher than the highest beach in that profile. This difference of elevation was attributed to the fact that the highest and oldest beach was principally composed of glacial-erratic material, which along the coast was generally so sparse that its concentration required for beach-making (by undertow and downdrag) was delayed until the land had risen several tens of feet. On that assumption, the highest shoreline in the wave-washed belt, an important element in the epeirogenic spectrum, must be established from the upper limit of wave-washing, after due allowance is made for the range of swash and spray-fling. In fact, the marks of the highest shoreline as determined in 1900 are, at the identifiable localities mentioned in the Tanner book, regularly 20 feet to 60 feet higher than the respective highest beaches as leveled by Tanner.

The present writer has difficulty in accepting Tanner's conclusion that all the high Torngat Mountains of northern Labrador were completely overwhelmed by the last (Late Wisconsin) icecap. During the 1900 exploration, traverses of many miles were made over mountains and broad valleys north of Nachvak Fiord. Above the 2,100-foot contour neither the *roche moutonnée* forms nor striations nor erratic material of the kinds and distribution expected, if the whole region had been covered by ice, were

found. Below the 2,100-foot level the effects of powerful local glaciers were conspicuous, but above it similar effects were observed only in cirques and in the troughs leading from cirques. The utter contrast between the firm, fresh, gray ledges of gneisses and schists below 2,100 feet with the deeply rusted, thoroughly frost-shattered Felsenmeer of gneisses and schists above that contour, and continuing to summit after summit, is described in the old field notes and is still vividly remembered. The contrast cannot, of course, be explained by any essential difference of postglacial climate above and below the 2,100-foot level. It may be added that the ice-molded surface found by Odell on one 4,700-foot summit of the central Torngats, farther west, may indicate, as Odell himself remarks, that pre-Late Wisconsin ice was there ½ mile thicker than it was along the Nachvak Fiord but by no means proves that the eastern half of the Torngat Range was entirely covered by the last Wisconsin icecap. Moreover, there seems to be no published evidence that this belt was wholly submerged by any icecap older than the Wisconsin.

Tanner doubts that the postglacial upwarp of the Labrador peninsula still continues. He discounts the testimony of fishermen of the northeast coast, who have insisted that the water on rock ledges opposite their "tilts" on the shore has somewhat shallowed during the lapse of fifty years or so. If his contention is sound, it would seem necessary to suppose that the coastal belt lies outside (northeast of) any hinge line analogous with the Whittlesey hinge line of our Midwest. In such case the contemporary dynamics of northeastern Labrador would differ from that of the Great Lakes district or that of the Baltic region (see Witting below), where present-day warping of the earth's crust has been demonstrated. Clearly, the question of contemporary uplift of Labrador deserves further discussion, and, above all, effort should be made to settle it ultimately by the use of well-established bench marks and also by repeated precise levelings.

Another significant contribution to knowledge is R. Witting's "Landhöjningen utmed Baltiska Havet under åren 1898–1927 (Die Landhebung dem Baltischen Meere entlang in den Jahren 1898–1927)," published in *Fennia 68*, No. 1 (1945) (pp. 1–40). The main text is written in Swedish; an extended summary in German is added. This paper gives the results of its author's determination of the contemporary upwarping of the Baltic region during the thirty years ending in 1927. He had measured the uplift of the same region during fifteen years ending in 1912, with his findings published in *Fennia 39*, No. 5 (1918). His map showing lines of equal uplift between 1888 and 1912 (reproduced on p. 62 of the present writer's *The Changing World of the Ice Age* [New Haven, 1934]) illustrated the differential nature of the movement, the zero-line following roughly the south coast of the Baltic. Thence, northward, eleven other lines, spaced so as to represent successively greater uplift in the amount of 1 millimeter per annum were drawn; the map indicates upwarp increasing to a maximum at the locus of the greatest loading by the Fennoscandinavian icecap. The zero-line, the 1-millimeter line, and the 2-millimeter line of this older map are strongly sinuous. When the data of the thirty-year interval were reduced, that sinuosity was found to disappear, as indicated by the map, Figure 7, of the 1945 paper, where it is also seen that the zero-line is situated somewhat farther north. Witting points out that the new map is intended to give relative changes of level; the absolute changes cannot be stated until knowledge is had regarding any eustatic shift of sea-level between 1888 and 1927.

The outstanding feature of the map is the close approach of the lines of equal uplift with the mapped isobases for the warped shoreline of the Littorina Sea, with the isobases for the marine limit in Fennoscandia, with the lines of equal uplift representing changes of level at bench marks cut in bedrock in 1800, and also with the lines of equal uplift of the land north of the Gulf of Finland, as demonstrated by precise leveling (see map on p. 315 of the present writer's *Strength and Structure of the Earth* [New York, 1940]). It is hard to dispute Witting's conclusion that the contemporary upwarping of Fennoscandia follows the same general pattern as that of the Late Pleistocene upwarping. Can there be any doubt that the deformation of the Fennoscandinavian crust is a result of isostatic adjustment for removal of its last great load of ice?

The isostatic recoil of a deglaciated region is ably discussed in still a third paper (in English)—this by E. Niskanen with the title "On the Deformation of the Earth's Crust under the Weight of a Glacial Ice-Load and Related Phenomena" (*Annales Academiae Scientiarum Fennicae*, Ser. A, Vol. III, *Geologica-geographica*, No. 7 [Helsinki, 1943], pp. 1–22). It is a dis-

cussion based on the theory of spherical harmonics. Niskanen assumes: (1) the truth of the Airy-Heiskanen theory, whereby he explains the depression of Fennoscandia under the weight of the last icecap and the recoil after the disappearance of the ice; (2) the earth's "crust" to be 63.7 kilometers (1 per cent of the earth's radius) or, alternatively, 31.85 kilometers in thickness; having a density of 2.7 and resting on a 1,200-kilometer earth-shell composed of incompressible "eclogitic" fluid with density of 3.3; and (3) thicknesses of ice (density 0.9), supposed uniform, at 2,000, 2,500, and 3,000 meters.

The calculated degrees of basining of the crust under these various loads are presented in tabular form. There is also discussion of the special, arbitrarily chosen, case of an icecap having a radius equal to 9° of earth-arc, the thickness of ice from the center out to 6° being uniformly 2,000 meters and that between 6° and 9° being uniformly 1,000 meters.

It was found that the crustal subsidence at the center of a 30° cap (of uniform thickness) would be nearly the same as that expected if the crust had no strength. However, owing to its actual strength the depression of the crust at the edge of the cap would be only about 45 per cent of that amount, and the basining would extend several degrees of earth-arc beyond the edge of the cap. Much less extended caps would have contrasted effects. At its center the 6° cap would cause the crust to sink by an amount only about 87 per cent of the amount expected if the crust had no strength, the corresponding percentage at the edge of the cap being 40. For a 9° cap the respective percentages would be about 96 and 44. Niskanen found the percentages to be about 50 and 30 in the case of an icecap with a diameter of 5° (550 kilometers). He generalizes as follows: "These results show us clearly, how sharply the depression decreases when [the radius of the icecap] diminishes. This result is in full accord with Jeffreys' assumption as he states: 'Thus we should expect that the compensation of inequalities of horizontal extent small compared with 2000 km would be incomplete.' The limit put forward by Jeffreys with us corresponds to the value [of icecap radius of] 9° = 1000 km." With his underlying assumptions, Niskanen finds no difficulty in explaining the large gravity anomalies in volcanic islands like Hawaii and Madeira and the long belts of anomalies discovered in Hindustan.

Besides the crustal deformation the author discussed the enforced changes of sea-level. He corroborates the view that, before the basined Fennoscandinavian sector began its plastic recoil in Late Pleistocene time, the sea-level itself was considerably deformed in the same sense. For example, a 2,000-meter, uniformly thick icecap with radius of 9° of earth-arc would depress the crust 526 meters at the center of the cap and 239 meters at its edge. Because of the negative attraction of that basin, sea-level at the center would be depressed below its preglacial position 118 meters if the thickness of the "crust" is 63.7 kilometers, and 110 meters if the thickness is 31.85 kilometers. The corresponding depressions of sea-level at the edge would be 48 meters and 66 meters. Hence, in estimating the amount of uplift of the older beaches in the Fennoscandinavian region, one must allow for the fact that the deformation of sea-level must cause an important addition to the effect of crustal deformation. Niskanen notes how such estimates are further complicated because of the eustatic rise of sea-level while those older beaches were being formed.

The author was naturally conscious of the arbitrary nature of his fundamental assumptions. He believes that the facts of observation are better accounted for if the "crust" has a thickness only half the maximum (63.7 kilometers) assumed in his discussion. He expresses his willingness to accept Jeffreys' conclusion that the thick earth-shell below the "crust" has a small degree of strength, thus demanding less sinking under ice-load than that computed when that shell is assumed to be "fluid." In spite of all qualifications, this paper must be rated as another praiseworthy and useful guide to thought about the meaning and mechanism of "isostatic adjustment."

In his paper on "Gravity Formulas Derived by the Aid of the Latitude and Longitude Zones" (*Annales Acad. Sci. Fenn.*, Ser. A, Vol. III, *Geol.-Geog.*, No. 1 [1941], pp. 1–19) N. Luoma has made another attempt to answer the question as to whether the earth's equator (sea-level figure) is elliptical. He used the free-air gravity anomalies determined at 7,138 stations. These were grouped in 10° zones of longitude and also in 10° zones of latitude; and from the groups of every zone gravity formulas were derived. Luoma's conclusion runs as follows: "The results of the various latitude zones do not agree well with one another. But we must add that in omitting the disturbed areas the observed gravity anomalies seem to be in rather good har-

mony with the triaxiality of the equator. It seems to be possible that the difference . . . . of the long and short equator axis is about 150 to 250 m. and that the long equator axis lies about 0° to 20° west of Greenwich."

E. Niskanen discusses the same problem in his "Gravity Formulas Derived by the Aid of the Level Land Stations" (*Annales Acad. Sci. Fenn.*, Ser. A, Vol. III, *Geol.-Geog.*, No. 10 [1945], pp. 1–16). He used isostatically reduced anomalies of the Northern Hemisphere and only those at stations in "plain" area and under 300 meters in height. He also deduced triaxiality for the sea-level figure of the earth, the long equatorial axis exceeding the short axis by 293 meters and emerging about 4° west of the Greenwich meridian. In his summary he remarks: "In the opinion of the writer it seems natural to assume that the triaxiality is caused by the overcompensation of the continents and of the oceans." He of course agrees with all other workers on the earth's figure that final conclusion regarding the ellipticity of the equator is impossible until thousands of new, well-distributed measurements of gravity are made in the Southern Hemisphere.

Finally, three important discussions of gravity anomalies in as many regions of special interest to structural and dynamical geologists will be mentioned. Brief summaries of these can hardly be of much real value; each should be studied carefully from cover to cover. The three memoirs bear the titles:

1. "On the Structure of the Earth's Crust in the Neighbourhood of the Ferghana Basin," by V. Erola (*Annales Acad. Sci. Fenn.*, Ser. A, Vol. III, *Geol.-Geog.* No. 3 [1941], pp. 1–77);

2. "On the Isostatic Structure of the Earth's Crust in the Carpathian Countries and the Related Phenomena," by L. Tanni (*Annales Acad. Sci. Fenn.*, Ser. A., Vol. III, No. 4 [1942], pp. 1–100); and

3. "The Gravity Anomalies on the Japanese Islands and in the Waters East of Them," by W. Heiskanen (*Annales Acad. Sci. Fenn.*, Ser. A, Vol. III, No. 8 [1945], pp. 1–22).

R. A. Daly

The Geology of Missouri. By E. B. Branson. ("University of Missouri Studies," Vol. XIX, No. 3 [1944].) Pp. 41; figs. 57; pls. 49. $3.00.

This volume, the second work published under this title by the author, is devoted principally to the stratigraphy and paleontology of Missouri. It takes up in chronological sequence all formations from the pre-Cambrian through the Tertiary and is concluded by sections on the Pleistocene; topography; structural and economic geology, parts of which were written by Chauncey D. Holmes, Cornelia Cameron, and W. D. Keller; and an extensive Bibliography of nearly one hundred pages. The plates, in halftone, all illustrate Missouri fossils. About one-third of them were taken from unpublished papers and illustrate many unnamed new species. The others are mostly reproductions of plates previously published by Branson and associates. The figures include excellent outcrop photographs; a series of outcrop maps, some of which illustrate paleogeographic interpretations; several correlation charts, etc.

Branson's extensive field observations during his many years' residence in Missouri have contributed much to the preparation of this work, but sections devoted to the pre-Devonian and post Lower Mississippian formations are based largely upon the published investigations of others, to which references are made. Branson has been particularly interested in the Devonian and Lower Mississippian rocks of Missouri; and his discussions of these formations present his views regarding correlations and other interpretations, which are not entirely acceptable to some other stratigraphers and paleontologists. This field appears to be beset with important and as yet not completely solved problems, and more objective considerations would have been advantageous.

In general, the treatment of each formation begins with a statement regarding the derivation of its name and the distribution; followed by lithologic description, often including a measured stratigraphic section; discussion of its stratigraphic relations; a list of fossils; and concluded with a paragraph on age and correlation. Inasmuch as nearly ninety named formations are considered and more than one-third of the text in the stratigraphic portion consists of fossil lists, the individual discussions are necessarily brief, and some are hardly adequate. Most of the fossil lists are composite. Generally, sources of the lists are given, but there are no locality data. The author admits (p. 402) that many of the identifications are possibly incorrect. Under these circumstances it may be questioned whether the fossil lists are deserving of so much space. They are intended to be complete, but some inadvertent omissions occur.

This volume is an important compendium of

information on the geology of Missouri and will prove most useful to all geologists interested in that state. Perhaps its chief deficiency lies in inadequate presentation of facts regarding the distribution and detailed stratigraphic relations of some formations. Interpretation of some episodes in the geologic history of the state are presented at various places in the text, but the data do not make possible the reconstruction of a connected history. The very brief section on structural geology is almost entirely descriptive and gives little aid in this direction. Very little information concerning subsurface geology is presented.

J. M. W.

Principles of Physical Geology. By ARTHUR HOLMES. New York: Ronald Press Co., 1945. Pp. 509; figs. 262, pls. 95.

Every author who prepares a textbook knows that the greatest measure of criticism will come not from the students who use the book but from his teacher-colleagues who will peruse it. Teachers of introductory geology will view with utmost respect Holmes's masterly treatment of the *Principles of Physical Geology* for the beginning student. The author's colleagues, after inspection of the book, will feel that little that is essential has been omitted.

The plates mentioned on the title-page in many instances carry two halftone views, and some of the text illustrations involve four or five diagrams. Thus, the author has endowed a book of 509 pages, each page covering an area of $4 \times 6\frac{1}{4}$ inches of type, with at least 425 photographs, line drawings, diagrams, sections, maps, and tables. Through these visual aids to student understanding the American teacher will roam, rather expecting that the European Continent and the British Isles will have furnished a British author with such a plethora of geological illustration that distinctive North American material will hardly find room.

Dr. Holmes, however, has chosen his photographs so judiciously from many parts of the globe that the American reader will find over forty views of well-known North American physiographic features. Included are the Grand and Bryce canyons, Niagara and Yosemite falls, the South Dakota Bad Lands, and Rainbow Natural Bridge. Appalachian mountain structure, the faults and fault movements of the Pacific Coast, the terraces of the Frazier and the delta of the Mississippi River, ice erosion in the Yosemite Valley, and the development of the Great Lakes are all given illustration and comment. He will find that the contributions of Daly, Dana, Davis, Dutton, Gilbert, and others have not been overlooked or ignored. The bibliographies at the ends of chapters contain references to the works of Ford, the Fentons, Willis, Lahee, Schuchert, Dunbar, Lobeck, Von Engeln, and to many other American authors.

In the textual presentation a chapter on continental drift; three chapters on the challenge of earth movements and of mountain building; considerable emphasis on isostasy; and the mathematics involved in determination of earthquake origin, in thermal dynamics, and in the formulas of wave motions stand out in some contrast from the customary treatment of such subjects in textbooks of beginning geology.

The book seems to have been proofread with great care, and but a few typographical errors appear. The paper selected by the publishers does away with the glare of reflected light at night, which often is a serious matter to students. On the other hand, this paper possibly is responsible for the poor reproduction of some of the halftones. The book commands hearty approval and praise for the thorough manner in which the subject is developed. Some American teachers, in using it, probably will need to plead for an extension of the time allotted to geology in their college programs in order to treat the subject adequately.

JOHN R. BALL

Geology as a Profession. ("National Roster of Scientific and Specialized Personnel, Vocational Booklets," No. 1.) Washington: United States Government Printing Office, 1946. Pp. 19. $0.10.

This useful booklet has been prepared by Miss Ann R. Taylor, working under the direction of Dr. W. T. Read, with the advice and assistance of many geologists. It gives the subdivisions of the geological profession, the working conditions and types of employment, the opportunities for women, the related fields of employment, beginning jobs, advancement and conditions of employment, postwar outlook in the profession, and the qualifications and training, and makes suggestions as to how to get a start. The booklet is attractively illustrated. It will be of special value to advisers of young students and, while written primarily from the employment point of view, will also give those

entering the profession a condensed and business-like summary of what they may expect.

Copies may be obtained from the Superintendent of Documents, United States Government Printing Office, Washington 25, D.C.

R. T. C.

Mineral Resources of the British Commonwealth. London: Royal Society, 1946.

During the latter part of June and the first week in July the Royal Society of London held an Empire Scientific Congress dealing with scientific subjects of all kinds. A prominent place was given to discussions on the mineral resources of the British Commonwealth and the need for improved surveys. Copies of the following papers have been received by the *Journal of Geology:*

1. "The Need for a Co-ordinated Survey of the Mineral Resources of the Empire and for Operations on a Much Larger Scale than Hitherto," by Sir Thomas Holland.

2. "The Need for the Survey of the Mineral Resources of the Empire on a Much Larger Scale than Hitherto and for More Up to Date Methods," by Professor E. S. Hills.

3. Same title, M. S. Krishnan and D. N. Wadia.

4. "The Resources of Mineral Raw Products in the Union of South Africa," by Dr. L. T. Nel.

5. "Detailed Geological Mapping and New Zealand Mineral Resources," by E. O. Macpherson.

6. "The Mineral Industry of the Union of South Africa," by S. H. Haughton.

7. "The Need for a Co-ordinated Survey of the Mineral Resources of the Commonwealth (General and Special Recommendations)."

These are short papers of a dozen pages or less. Copies of particular speeches may be obtained by writing to The Secretary, The Royal Society, Burlington House, London W. 1, England.

R. T. C.

INDEX TO VOLUME LIV

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